UNDERSTANDING THE RF PATH

CommScope: understanding the RF path

Chapter 1

Introduction:
Welcome to RF communications

As a trusted advisor for communications networks around the world, **CommScope** invests in people as much as our products and our industry. Our comprehensive training and education programs, participation in working groups on specs and standards, educational conferences, and extensive research are long-standing traditions that benefit everyone in our industry.

That's why we're pleased to present this book on the fundamentals of radio frequency (RF) communications for the wireless industry. We hope this valuable information will help foster a greater understanding of, and appreciation for, the technology, science and business behind modern RF communications.

The technologies and theories explored here are technical in nature, so we have made every effort to make the science of radio systems more accessible for a wider audience—whether you are an engineer or simply someone who works in this industry and wants to learn more about the basics of how RF communication works, including the issues involved in the planning, deployment and maintenance of communication networks.

Let's start by taking a look at the storied history behind the technologies that have shaped our on-the-go, wireless world.

RF systems, then and now

Wireless communications systems have been in commercial use since the 1940s. Some of the earliest implementations included community repeaters, paging systems, point-to-point links and specialized mobile radio (trunked) systems. More recent innovations and uses of the RF spectrum include cellular radio networks, which originated in the 1980s and now drive the cell phone and mobile device industry. Even more recent evolutions have given us familiar names like WiFi and WiMax, which let you connect to a network anywhere in your house, or virtually anywhere you go.

The shared link

This storied list of applications is incredibly diverse in purpose and design, yet every item shares at least one unique characteristic: they all utilize radio frequencies between 30 MHz and 2.6 GHz to move information between base locations and remote users.

The chain of components required to make this movement of information possible is a complex and varied one. As a proud supplier to the world's communications networks, **CommScope** is uniquely able to explore and explain these components, how they work, and more importantly, how they work together.

Doing our part

CommScope goes to great lengths to provide the best possible solution for every application. For simple or complex RF communications systems, each part chosen by an engineer must fulfill a specific role, determined by the expectations and limits placed on the installation itself. This book will explore several common components and how they interact, including:

- Antennas
- Coaxial cables
- Filters
- Duplexers and diplexers
- Amplifiers
- Remote radio heads
- Enclosures
- Power backups

... and many others

RF communications: the early years

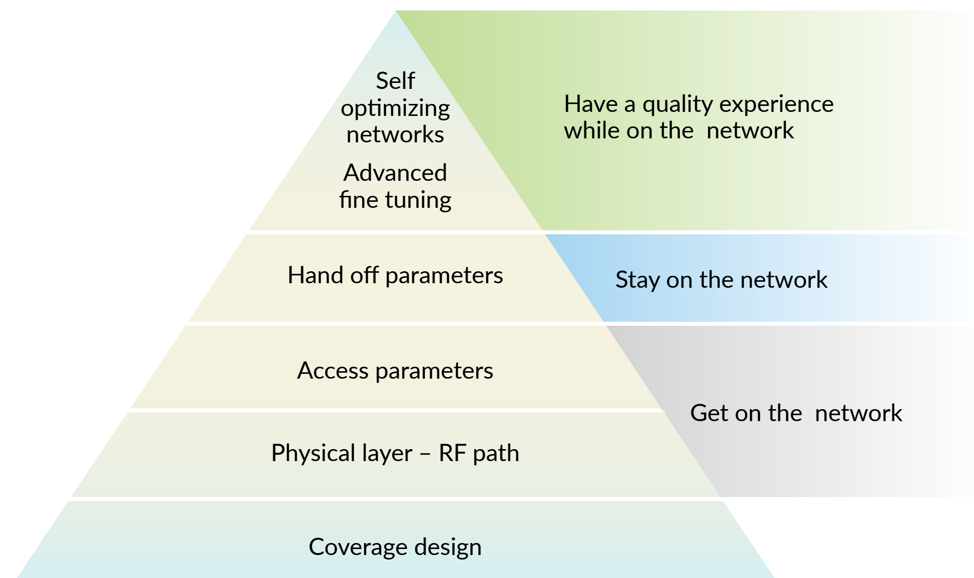
While the full story of RF communications is far from complete, the capabilities of modern RF technologies exceed the wildest dreams of the field's earliest pioneers. While we are all familiar with—and indeed, take for granted—living in a globally connected world, the early systems that laid the foundation for our networked existence were much less powerful.

The first RF systems featured a base radio using an omnidirectional antenna to communicate with one or more mobile users. Then, as now, the effective coverage radius of that base radio was limited by certain characteristics, such as RF power, antenna height, and the sensitivity of mobile receivers that were vulnerable to thermal noise and other interference sources. These systems were also limited by the fact that certain frequencies could only be used once in a particular geographical area. Once a mobile user left that area, no communication was possible.

The engineers of AT&T Bell Laboratories envisioned a future that would require much higher RF capacities to service thousands or millions of users at once. To deliver this future, they developed the cellular concept: a wireless network that uses lower antenna heights and transmission power levels to create limited-radius coverage areas that used and reused the same frequencies within its coverage area. Voice and data calls could be seamlessly handed off to neighboring cells as the user moved from one coverage area or cell to the next. The close-proximity reuse of radio channels is the fundamental concept of cellular telephones, and this is how today's wireless networks carry enormous traffic loads in spite of limited spectrum. The data riding these RF frequencies could be voice, data, or a combination of both; by intelligently managing and reusing the limited available bandwidth, the amount of available service increased by many orders of magnitude.

The business case for technical expertise

Cell providers monitor key performance indicators within their territories to identify coverage problems and assure customer satisfaction. These indicators include quality of service (QOS), dropped calls, failed access attempts, and other criteria. Their engineers are on the front lines of this battle for quality and constantly optimizing network performance as traffic grows. There are sophisticated parameters and advanced settings that help the RF engineer optimize a wireless network. However, successful wireless network optimization requires a solid foundation of physical components across the RF path (figure 1.1).



1.1: The interconnection of technology, design and optimization

The tuning and optimization of parameters can never be maximized without a high-performance RF path implemented with top-quality RF components. Conversely, wireless systems with weak RF paths perform poorly, resulting in expensive problems on both the operational and customer service fronts. Once a network is active, taking down a part of a cell network for maintenance is a costly and disruptive interruption; and, in most cases, one that could have been prevented by a better understanding of the site's requirements and the component choices available.

The path begins

Now that we understand the importance of foresight in planning, and insight in selection, we can begin this brief exploration of the many ways a modern RF communications network can come together. Thank you for joining **CommScope** on this journey.

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Chapter 2

Where RF theory meets best practices:
Cell site development and construction

Building a new cell site raises some of the same questions as building a new house, such as deciding what materials to use, who to entrust with the construction, and how to get the best results for your money.

Of course, these problems are magnified when applied to cell site construction because there are so many different people, companies, municipalities and regulatory agencies involved. It takes a lot of experience to plan for every obstacle. That's why **CommScope** offers the following proven recommendations.

These general guidelines are the result of decades of successful, practical field work. While no guide can cover every aspect of cell site development, we'll cover the most commonly experienced technical issues here.

Service company
A cell site development partner responsible for actual construction on the site, including antenna towers, concrete footers and pads, security fencing, and equipment shelters.

You will work with several different companies and agencies in the process of developing your new cell site. You must be able to count on their competence and expertise. For each stage of development, you should become familiar with the challenges and requirements each partner will face. Knowing these factors will help you judge how well your partners are doing their work and the impact those factors will have on your network when the project is done.

Step one: choosing a service company

A ***service company*** will help you build the actual structure of your cell site. This includes the tower, shelters, cabinets, and other physical infrastructure to support the site's operation (figure 2.1). This can involve heavy, demanding construction work and the precision required by modern cell networks means a lot can go wrong at this stage.

2.1: A services company building a cell site tower

As with building any structure, it pays to research your construction company in advance. Here are some of the key facts you should learn before selecting your services company:

- **How long has the company been in business, and in the wireless field?** This is one of the first questions to ask. Experience matters as much as, if not more than, expertise.
- **How many employees do they have? How many of them work in the field and how many in their home offices?** Their staffing levels can directly affect how they handle your project.
- **How financially sound is the company?** For legal and logistical reasons, it's critical that they don't disappear in the middle of construction. Plus, they will need to maintain a certain minimum cash flow and credit to procure materials.
- **What are their expected payment terms?** Some require payment within 30 days. Others may allow as many as 90 days. Make sure their terms work with your cash flow, too.
- **What is their recent bond history?** For everyone's protection, all craftsmen in the field should be bonded. Looking at their bond history can give you a good picture of how well they perform.
- **What kind of insurance do they carry?** The company should offer to share their certificates of insurance. It's also smart to request a report on their recent claims history.
- **How does their safety plan hold up?** Unfortunately, some companies keep a generic plan on file simply as a token compliance effort. Speaking with the company's safety manager will tell you if they really understand the written plan.
- **What's in their OSHA logs?** The Occupational Safety and Health Administration (OSHA) monitors workplace safety; your potential services company should have a log of recent incidents, claims and actions. As a minimum, the previous three years should be reviewed for diligence and completeness.
- **Are their field employees properly certified?** All field employees should carry current certifications for first aid, CPR, the OSHA 10-hour training course, Competent Climber and Tower Rescue operations.
- **Is their gear properly certified for safety?** You should request copies of current climbing gear inspection certificates.
- **How is their workplace recordkeeping?** To see what you could expect for your project, ask to see their job site analysis worksheets.
- **What kind of vehicles will they be using?** If they use vehicles regulated by the Department of Transportation (DOT), request a copy of the DOT Carrier Safety Measurement System (CSMS) rating. Prior to 2011, this rating was called SafeStat, and some companies may still refer to it by that name.

In general, finding the answers to these questions is simply a matter of thorough due diligence. With so many certifications and other qualifications in play, you can see how important it is to know your services company partner as well as possible.

Coaxial cable
A type of cable featuring an inner conductive core, an outer conductive layer, and a dielectric, or insulating, space between them. Coaxial cable connects antennas to their base stations.

Step two: choosing coaxial cable and connectors

Efficient cell site operation relies on the precise pairing of components. As we will discuss in detail in chapter 3, certain cable types are designed to work with certain antennas. As we will explore in chapter 7, those cables must interface with their systems via connectors built for certain frequencies and power levels (figure 2.2).

An out-of-specification component or an improper installation of the correct component can cripple an entire system. For this reason, it's wise to contract with skilled engineers for the installation.

2.2: Coaxial cable examples; different types are available for different applications

Handling the cable and connectors during these installations is a delicate business. In general, observing these tips can help assure a trouble-free installation and dependable, long-term operation:

- **Use the right tool for the job.** Using the appropriate cable prep tool, usually available from the cable's manufacturer, is the only way to cut and prep cable ends for use in connections. Never use a saw; they leave metal filings behind, which cause poor electrical performance and problems with passive intermodulation (PIM).
- **Watch those tricky curves.** Different cable types have different degrees of allowable bend radii, or flexibility, so you must observe the manufacturer's prescribed bend radius for your particular cable. Bending too tightly can lead to poor electrical performance and failure in the RF path.
- **Keep your cables consistent.** If at all possible, use RF jumper cables from the same manufacturer to make those tight connections. Doing so provides consistent electrical performance and guarantees PIM performance.
- **Ensure proper cable support.** Manufacturers publish specifications describing how to support lengths of cable, both vertically and horizontally. Your specific guidelines will depend on your cable's construction, size and weight. If possible, use support clamps from the same manufacturer to avoid damage to the cable and loss of performance. Using third-party clamps may also invalidate your warranty.
- **Lift smart.** Getting cables up an antenna tower is difficult. Fortunately, using the correct hoisting grip will let you put that cable where it needs to be without damaging it. Hoisting grips come in several types and sizes, so make sure yours matches your cable's specifications.
- **Go to ground.** Grounding the cable is very important to prevent damage from lightning strikes. Best practices dictate at least three grounding points: at the top of the tower, at the bottom of the tower and just outside the entrance to the outbuilding, shelter or cabinet.
- **Put on the pressure.** Air dielectric cables use an air-filled gap to insulate the inner and outer conductors of a coaxial cable (chapter 7). This gap must be pressurized, like a bicycle tire, for the cable to hold its shape and prevent damage to the conductors inside. When installing air dielectric cable, it must be pressurized immediately. Leaving it overnight can lead to moisture condensation in the cable, which will degrade performance and is almost impossible to remove once introduced.
- **Finish with the seal of approval.** Connectors are particularly vulnerable to infiltration by weather and moisture. As soon as the connections are made, you should weatherproof them. Butyl tape is the preferred method, but in tight connection spaces, like those atop the antenna tower, you can opt for heat-shrink tubing applied with a heat gun.

By following these recommendations, you can help ensure that your cell site will operate at peak efficiency with minimal maintenance.

Electrical tilt antenna
An antenna fitted with actuators that can adjust its tilt relative to the ground. Changing tilt affects gain, or performance, of the antenna within defined geographical areas.

Step three: setting and troubleshooting remote electrical tilt antennas

Of the many ways you can improve performance from a cell site's antennas, a particularly effective method is beamtilt. It involves physically tilting the orientation of the antennas below the horizon, placing its greatest gain—its operational power—where it's needed most (chapter 3).

Efficiently changing the orientation of an antenna to realize this benefit is a matter of using electrical tilting mechanisms, or actuators, which can be operated from a remote location (figures 2.3, 2.4, and 2.5).

These mechanisms are controlled by an Antenna Interface Standards Group (AISG) Remote Electrical Tilt (RET) controller, which connects via AISG cables at the cell site for adjustment (figure 2.5).

2.3: An electrical tilt mechanism, or actuator, for a cell site antenna

2.4: A base station antenna (BSA) with integrated RET actuators

2.5: An example of an AISG RET controller module

As precision equipment, these tilting antennas can be a challenge to install and adjust properly. Getting the best result is a matter of understanding the software just as much as the hardware, but there are several ways to avoid common pitfalls:

- **Install the software first.** Before your crew goes to the cell site, install the manufacturer's software and become familiar with the controller's operation. This early training will help your team hit the ground running when they arrive.
- **Check for program updates.** Driver software for your electronic tilt actuator system is constantly updated to work with an ever-growing number of different antennas. Make sure your software is current by checking for updates on the manufacturer's website.
- **Understand the naming conventions.** To prevent onsite confusion, use conventions for the configuration of actuators that everyone will understand.
- **Test before installing.** For new installations, a little upfront effort can prevent big headaches later. Test the actuators, cables and other components before installing them on the tower. It's much easier to address problems when the components, and you, are on the ground.
- **Match antennas and tilts.** Not every antenna has the same tilt range, so be sure you select the correct one from the database before adjusting it. Each antenna's address is based on its product serial number, so be sure to keep a written record. You should double-check your tilts through tab reports generated by the controller.
- **Keep a spare cable on hand.** Bring a spare cable to the site in case you need to troubleshoot a non-reporting actuator. It's the fastest, surest way to tell if the problem is a faulty actuator or just a bad cable.
- **Check before tilting.** Before making any new tilt adjustments, pre-scan the other antennas to determine their tilt values.
- **Double-check your work.** After making the adjustment, you should perform a post-scan to confirm the new settings have been correctly applied.
- **Don't weatherproof cables and connectors.** Using electrical tape won't keep moisture out, in fact, it gives water a place to accumulate in the connector, where it can cause shorts.
- **Protect against lightning**. Lightning protection units should be installed at the base of the tower, or just before the cable enters the shelter or cabinet. Also, as stated above, it should be grounded in at least three locations: at the top of the tower, at the bottom of the tower, and just before entering the shelter or cabinet.
- **Don't splice in a ground lead.** Cutting into the jacket to attach a ground to the thin foil tape inside will cause water migration, damaging the conductors below the foil.
- **Go right to the source for cable.** It's considered good practice to purchase your cable directly from the manufacturer rather than obtaining it from a third party. Each manufacturer's system requires specific electrical conductors, and using a mismatched cable may lead to actuator failure, voiding your warranty.
- **Make the right connections.** The home run cable's male connector—the end with the pins—is the end that connects to the controller. Also, be careful not to cross-thread actuator cables at the controller or on the actuator itself. They should be hand-tightened only. Never use a wrench.
- **Cycle the actuators when you're done.** After addressing each actuator, cycle it fully to confirm there are no hidden problems.
- **Check for cable stress.** All cables should be free of stress and secured in intervals of 18 to 24 inches.

Thorough planning and clear procedures like these will ensure that your cell site reaches and maintains its maximum potential while also allowing you to make the proper adjustments as your network evolves.

Best practices always yield the best results

Like building a house, there are countless ways for things to go wrong when building a cell site—which makes it all the more important to work with a partner who has the expertise and experience you need to do the job right. **CommScope's** long history of expertise can turn your next project into your next success.

Chapter 2 summary

Cell site development and construction:

- Research and choose a reliable services company
- Know your cables and connectors
- Maximize gain with electrical tilt antennas

Chapter 3

Getting the signal across:

Base station antennas

Today, the quest for a stronger signal strength—or for some, any signal strength at al—has become a routine part of our daily lives. We're always searching for a way to get more "bars" on our cell phones or faster Wi-Fi connections on our computers. Whether you're at home, at work or on the go, you need good reception to communicate and good reception depends on antennas.

The antenna is one of the most critical parts of both transmitters and receivers, and often, it's the most visible. You can see big antennas mounted on tall towers, and small ones attached to Wi-Fi adapters or cell phones. Antennas come in all shapes and sizes because each one is built for a specific purpose. However, all antennas share a common link: they are the key to how well and how far communications can be shared.

CommScope invests significant research and resources in the development of reliable, high-performance antennas, technology and innovation to better support evolving networks around the world.

Antenna
The portion of an RF system that radiates radio energy into space and collects it from space.

Dummy load
A simulated power load applied to an electrical system for testing purposes.

What is an antenna?

At its most basic level, an *antenna* is the portion of a radio system that can:

1. Take radio energy from a transmission line and radiate it into space in a predictable pattern, and
2. Receive radio energy from open space and feed it back down the transmission line.

Antennas are surprisingly efficient in this line-to-space and space-to-line energy conversion process. In fact, when properly configured with the right components, antennas can yield 80 percent efficiency or greater—a remarkably high figure in engineering terms. By way of comparison, consider the common incandescent light bulb, which yields only 20 percent efficiency. This means that, of the amount of energy put into a bulb as electricity, only 20 percent of that energy is put out as light. An important consideration to maintain an antenna's extraordinary efficiency lies in the transmission cable that connects it to the transmitter.

Matching the line

To get maximum efficiency from a radio transmission's power, the antenna and cable must share certain characteristics to avoid wasted energy. For example, if a radio system uses an industry standard coaxial cable fixed at 50 ohms to connect the antenna and its transmitter, the antenna itself must rate reasonably close to 50 ohms as well.

Testing this configuration is a simple task. We connect the coaxial cable to the transmitter and place a 50-ohm *"dummy load"* on the other end to simulate an antenna. Using a watt meter will reveal two important factors that measure the efficiency of the system:

1. The amount of power entering the cable from the transmitter, and
2. The amount of power reaching the dummy load.

The difference between these two measurements represents the power lost in the line itself. The better matched the cable, the smaller the difference, and the more power reaches our simulated antenna.

If we reduce the simulated antenna's load from 50 ohms to just 25 ohms, 11 percent of the energy sent through the coaxial cable would be uselessly returned to the transmitter. That would yield very low efficiency unless we were to replace the 50-ohm coaxial cable with one rated at near 25 ohms, thereby restoring the balance. However, the 25 ohm cable would move mismatch to the source end where it connects to the transmitter.

Like water pouring through a funnel, the amount of throughput is dictated by the tightest portion of the route. In a radio system, the excess energy bounces between the transmitter and the antenna, which must reject all power above its capacity. This endlessly reflected power creates a measurable wave pattern in the cable, an effect called the voltage standing wave ratio (VSWR).

VSWR is the measurement of how well-matched a transmission line is to its antenna. Expressed as a ratio, a VSWR of 1.0:1 indicates a perfect match. Likewise, a VSWR of 1.5:1 indicates a 4 percent power reflection, which is another way of describing 96 percent efficiency, where 96 percent of the power output from the transmitter actually makes it to the antenna (table 3.1).

Voltage standing wave ratio (VSWR)
A measurement of the power reflected between transmitter and antenna in a transmission line that connects the two. This figure yields the system's transmission efficiency.

Calculating voltage standing wave ratio (VSWR)			
VSWR	Return loss (dB)	Reflected power (%)	Through power (%)
1.10	26.5	0.2	99.8
1.25	19.1	1.2	98.8
1.50	14.1	4.0	96.0
1.75	11.6	7.4	92.6
2.00	10.0	11.0	89.0

VSWR = $[1 + 10^{((\text{-Return Loss})/20)}]/[1 - 10^{((\text{-Return Loss})/20)}]$

3.1: Calculating VSWR, and some sample efficiencies

Velocity, frequency and wavelength

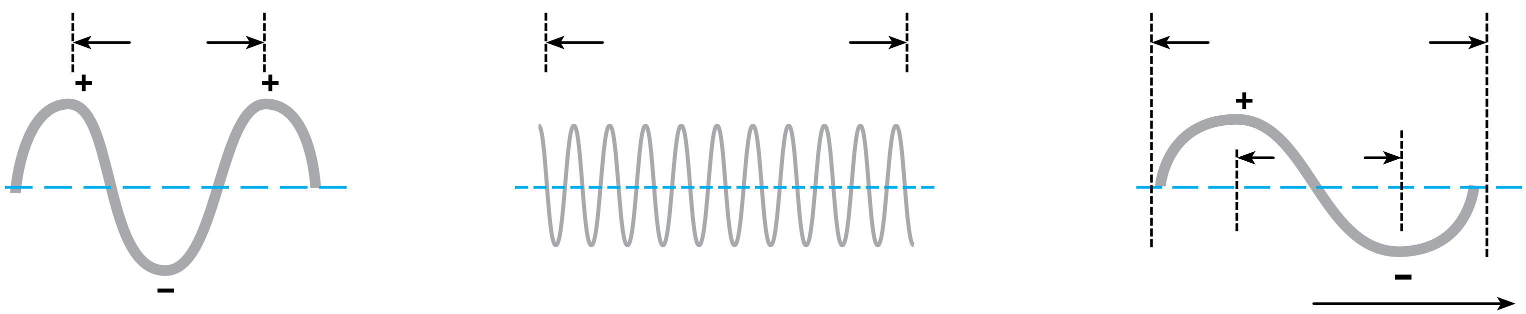
Like all forms of radiation, including visible light, radio waves travel about 186,000 miles, or nearly a billion feet, per second. Like other forms of radiation, radio waves oscillate, or flip back and forth, between plus and minus at a predictable rate. Each complete flip is called a cycle, and cycles are expressed in hertz (figure 3.2). Measuring how many cycles, or hertz, a signal oscillates per second gives us its frequency—literally, how "frequently" the signal oscillates in one second.

Knowing a signal's speed and its frequency, we can divide the first by the second to determine its wavelength—the distance the signal travels while completing one full cycle. Wavelengths are usually measured in feet or inches, and are useful in understanding what it means to be "in phase" or "out of phase," which we'll explore later in this chapter.

Antennas are two-way streets

In theory, antennas transmit and receive in precisely the same way; the same processes occur both ways. Only the direction is reversed. In actual practice, however, a number of complicating factors, particularly on the receiving end, can impact the efficiency with which the antenna operates.

To demonstrate, it is perhaps easiest to explore the most basic of antennas: the half-wave dipole.



A cycle completes itself traveling from plus to minus back to plus.

The number of cycles in one second gives the frequency.

The speed divided by the frequency gives the distance the wave travels in one cycle. This is called the wavelength.

3.2: Relationship of time, frequency, and wavelength

Half-wave dipole

The half-wave dipole radiator antenna, often just called a "dipole," is the most basic one used in two-way base station applications. It is essentially nothing more than a straight conductor made of wire, rod or tubing that measures exactly half of its assigned frequency's wavelength. A rule of thumb for determining the correct length is:

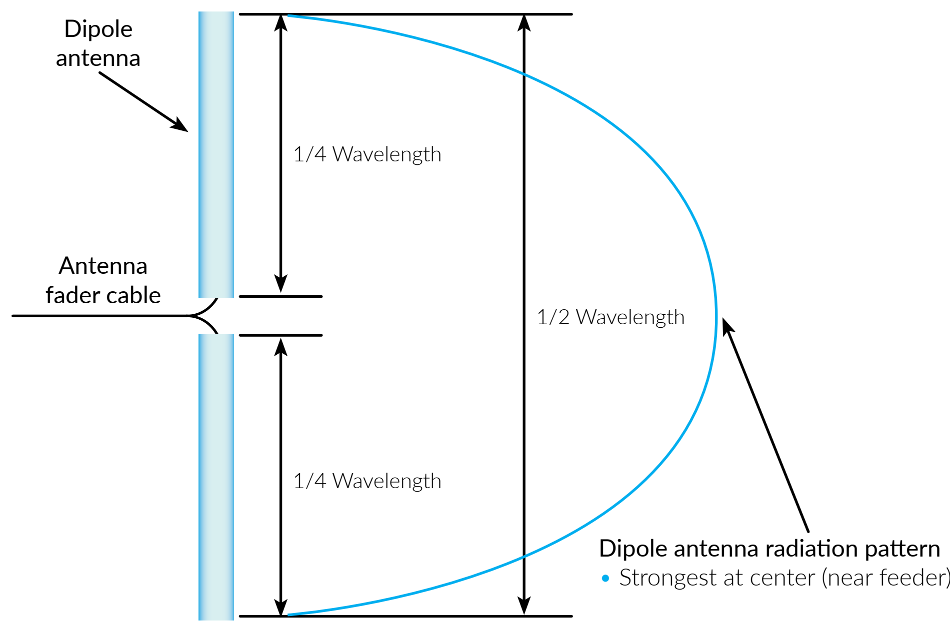
Length (in inches) = 492 divided by the desired frequency in MHz

As a result, dipole antenna length can be highly variable. It could be just 2.4 inches in length for a frequency of 2500 MHz, or 20 feet long for a frequency of 25 MHz. The table below provides more examples (table 3.3).

Generally, the feeder line is connected at the midpoint, so the antenna radiates at maximum intensity in the middle of the dipole. (figure 3.4).

Frequency (MHz)	1/2 Wavelength (inches)	Frequency (MHz)	1/2 Wavelength (inches)
30	196.8	800	7.4
50	118.1	900	6.6
74	79.8	1700	3.5
150	39.4	1900	3.1
220	26.8	2100	2.8
450	13.1	2500	2.4
750	7.9	3500	1.7

3.3: Half wavelengths of two-way frequencies



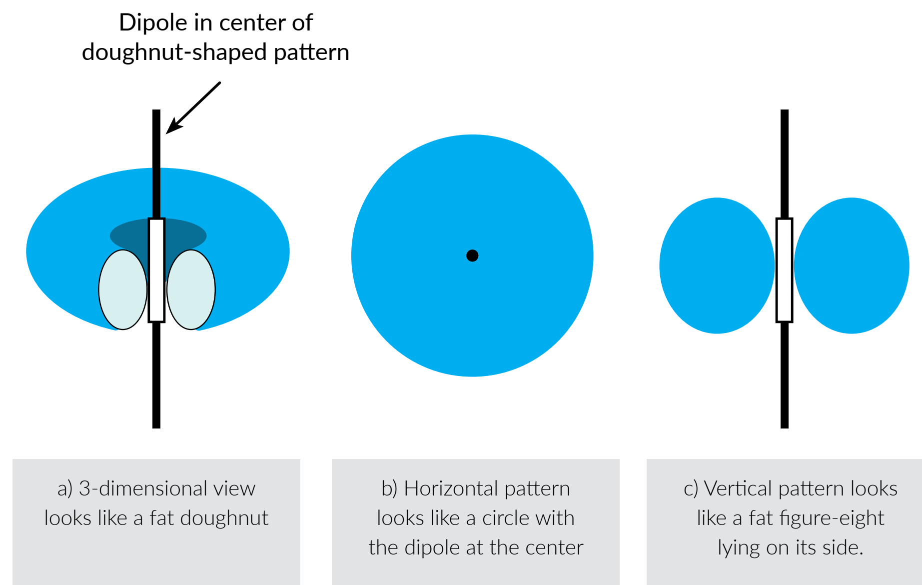
3.4: Dipole antenna construction and radiation pattern

Vertical and horizontal antenna radiation patterns

All antennas, regardless of polarization, have three-dimensional radiation patterns. If the pattern is extended in all directions equally, the resulting shape would be a sphere, with the antenna at its center. The polarization of the antenna determines which portion of that sphere represents an antenna's actual pattern. Slicing the sphere vertically yields a vertical circle while a horizontal slice would reveal a horizontal circle.

These theoretical descriptions of the two polarization patterns appear to be omnidirectional within their planes, but that's not quite the case. In practice, there are no truly omnidirectional antennas. Our example, half-wave dipole antenna, for instance, reveals the truth (figure 3.5). The pattern appears circular, like a doughnut, on a horizontal plane, but forms a figure-8 in the vertical plane.

As we will see later in this section, most real-world antennas consist of a vertical array of radiating elements and elevation pattern shaping has become quite important for interference minimization (figure 3.18).



3.5: Radiation patterns for a dipole antenna

Antenna gain

Using our half-wave dipole as our reference, we measure gain in decibels (dB). Decibels are used to compare one quantity of power to another. So, taking our dipole as our starting point, we say it has a gain of one, or that it has a value of 0 dB, as it has “zero difference” from itself. If we have an antenna with double the power of our reference dipole, we find that its power ratio of 2.00 yields 3 dB in gain (table 3.6).

Power ratio	dB	Power ratio	dB
0.10	–10	1.00	0
0.13	– 9	1.26	1
0.16	– 8	1.58	2
0.20	– 7	2.00	3
0.25	– 6	2.50	4
0.32	– 5	3.16	5
0.40	– 4	4.00	6
0.50	– 3	5.00	7
0.63	– 2	6.30	8
0.79	– 1	8.00	9
1.00	– 0	10.00	10

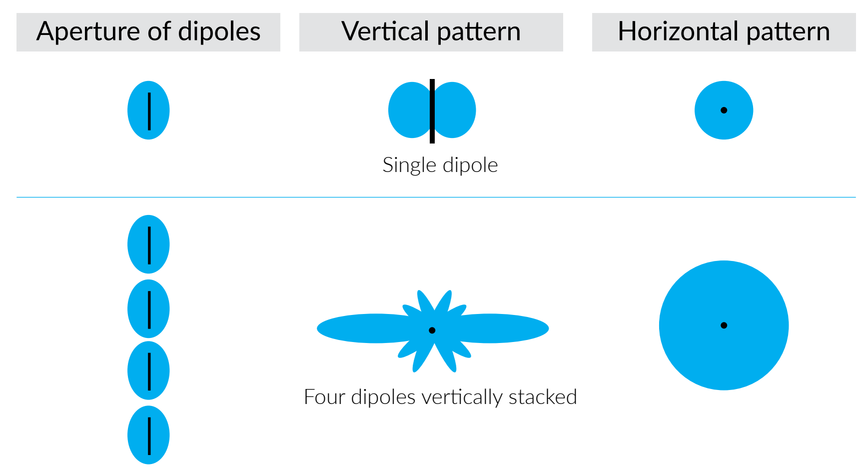
3.6: Deriving gain in dB from power ratios

Boosting gain

Theoretically, there are two ways to increase antenna gain.

1. We can increase the power or current density in the antenna so it will radiate its pattern with greater intensity. But as we discovered earlier, we cannot raise the power without fundamentally altering the mechanics of the antenna, cable and transmitter.
2. Alternately, we can change the radiation pattern, tightening its focus, so more of the existing power is directed where it will be used. This can be done without changing out hardware.

Consider again the circular, doughnut-shape pattern of our dipole antenna (figure 3.7). By “squashing” the doughnut vertically, we produce a denser, flatter, rounder pattern. As a consequence, the circle also grows larger as vertical space is traded for horizontal space. Since verticality is rarely of importance, this is a very profitable exchange.



3.7: This figure illustrates how stacking four dipoles vertically in line changes the pattern shape (squashes the doughnut and increases the gain over a single dipole). The area of the horizontal pattern measures the gain. The small lobes in the lower center section are secondary minor lobes.

In phase
Multiple antennas radiating together at precisely the same time and rate.

Omnidirectional pattern gain antennas

To achieve greater gain in this circular (or omnidirectional) pattern, we can stack multiple vertical dipole antennas above each other, as shown in figure 3.7. This increases the vertical size of the antenna. Then, we feed power to the dipoles in such a way that they add together at a distant point—again, with transmission lines matching their radiation power limits for greatest efficiency. By feeding equal amounts of power that arrive at each dipole at the same instant, the dipoles radiate ***"in phase,"*** or in synchronicity, for improved gain by virtue of its pattern.

This type of antenna is called a vertical collinear phased array, and it is the most commonly used type of base station antenna.

Aperture

Aperture, or beam width, determines the gain of an antenna. Like an adjustable nozzle on a garden hose, aperture describes the degree to which the signal is focused: the tighter the focus, the greater the gain within that area of focus.

Spacing of dipole elements

In a vertical collinear array, each dipole or sub-array of dipoles is connected in parallel to the common feed point by a separate transmission line. This means it's possible to locate the dipoles so that their vertical separation tightens overall aperture to boost gain. This separation is usually something less than a single wavelength of the assigned frequency being transmitted. Anything less tends to reduce the improvements in gain.

Feeding the array

In a vertical collinear array of two or more dipoles, the most common means of feeding power via the coaxial transmission lines are:

> **Parallel (shunt) feed.** Power is fed along individual lines to each dipole or sub-array of dipoles. Using matching transformers and junctions, the cables connect to the line running down the tower. This allows the array to be fed from the center, equalizing the effectiveness of each array element and preventing the beam tilt that affects series-fed installations.

In either application, the physical length of the aperture directly determines the amount of gain.

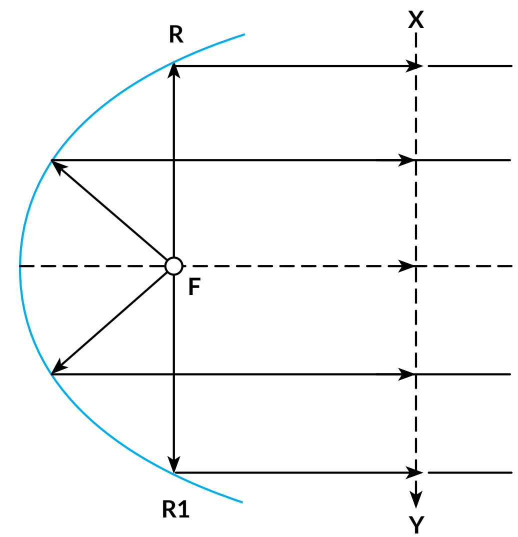
Directional gain antennas

While omnidirectional gain antennas like the vertical collinear array achieve greater gain by compressing its vertical pattern into a flatter circular shape, there are other types of antenna that modify their horizontal patterns to accomplish the same gain improvements.

Dipole and reflector

As we've shown, a vertical dipole antenna has a circular horizontal pattern. However, if we position it in front of a metal screen or wire mesh, we see that radiation going to the rear will be blocked (figure 3.8). If this blocked radiation is reflected off this screen, the horizontal pattern will no longer be circular, but directional.

If a dipole is positioned exactly one-quarter wavelength from this reflection screen, the radiation that would ordinarily go to the rear is redirected to the front to form what is called a directional lobe. It's the same effect as that of the reflective mirror behind a flashlight's light bulb, which redirects the circular light pattern into a single direction. The larger the screen, the greater the reflection and the narrower the directional lobe becomes—and just as the omnidirectional antenna increases gain by compressing vertically, this directional antenna increases gain by compressing horizontally and directing all its power in a single direction.

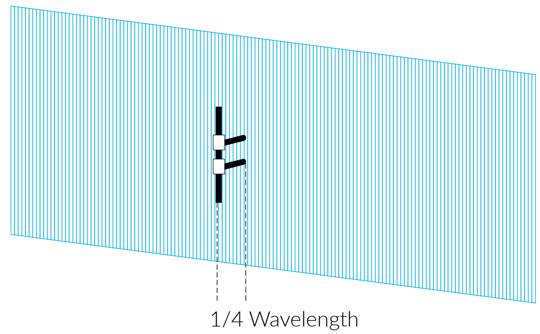


3.8: The omnidirectional pattern of a dipole can be made directional

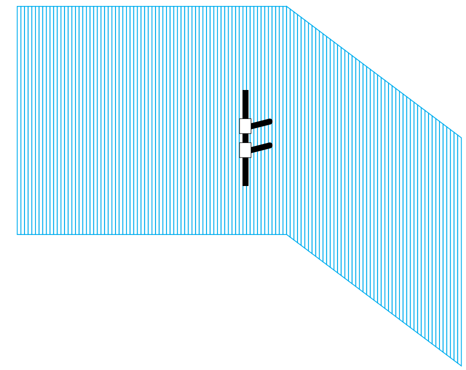
Corner reflector and parabolic reflector

Corner reflectors are right-angled V shapes, with their vertices spaced a certain distance from the dipole (figure 3.9). The resulting reduced beam width and the corresponding increased gain is determined by the size, shape and distance of the screen from the dipole.

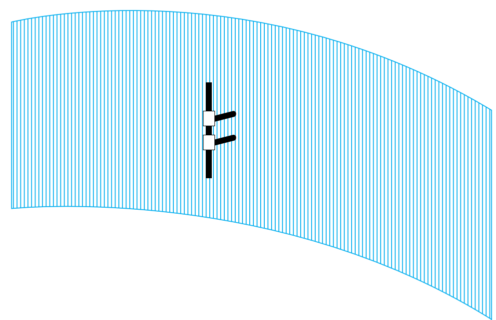
Modifying this corner reflector into a rounded bowl shape creates a parabolic reflector, with the dipole placed at its focal point. In either application, the reflector may be built of closely spaced rods instead of wire mesh, increasing the strength and reducing the wind drag of the reflector.



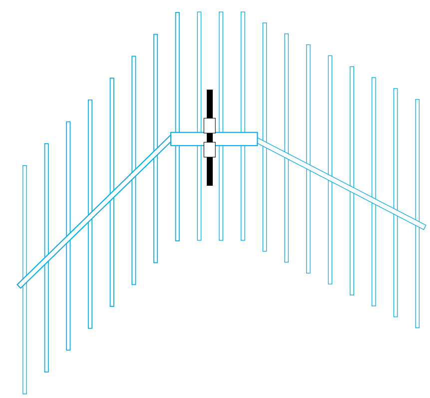
Flat screen
Radiation to the rear is blocked



Corner screen
The screen behind the dipole cuts off radiation to the back and reflects it forward to form a beam



Parabolic screen
The parabolic screen focuses on the beam



Corner reflector
Vertical rods replace the scree of the corner screen to make a reflector of stronger mechanical design

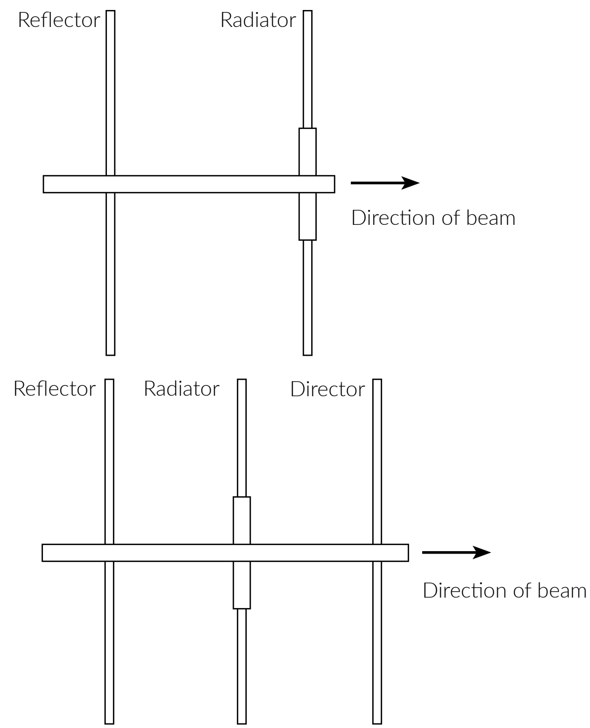
3.9: Dipole antenna reflector shapes

The Yagi antenna

Perhaps the most commonly used directional antenna is the Yagi antenna. The Yagi offers many variations and forms, but it generally consists of three elements (figure 3.10):

1. Radiator
2. Reflector
3. Director

These components are arranged such that the director is in the front, the radiator behind that, and the reflector behind both. Generally, the director is the shortest component, and the reflector the longest. The spatial relationships between the three elements determine the power that goes into the Yagi's directional lobe, and therefore also determine the Yagi's gain. It is an efficient and flexible design, offering high gain, low weight, minimal wind drag and modest cost, resulting in its popularity for two-way radio communications.



3.10: Two-element and three-element Yagi directional antenna

Yagi antenna
Also known as an Yagi-Uda antenna, this is a common type of directional antenna, first created in Japan in 1926 by Hidetsugu Yagi and Shintaro Uda.

The bandwidth factor

Another consideration in antenna construction is that of bandwidth. As we discussed in our description of the dipole, antennas must be built to lengths that are determined by their operating frequency wavelengths. As you may recall, the dipole antenna must be half the length of its assigned wavelength. However, it is possible to build an antenna that covers a range of frequency bands or bandwidth centered around a particular frequency.

Indeed, nearly every antenna in use today affords a fairly wide percentage of bandwidth. In fact, certain antenna designs in the 1900 MHz frequency range can offer over 45 percent bandwidth (1710-2690 MHz). These are known as ultra-wideband antennas.

The bottom line of antenna design

We've just covered the basics of antenna design, but it's important to keep in mind that there are no magic formulas or one "ideal" antenna configuration. Improving one aspect of operation always comes at the expense of another aspect. The best design is always one that is driven by the specific operational objectives of the antenna.

Cellular antenna concepts

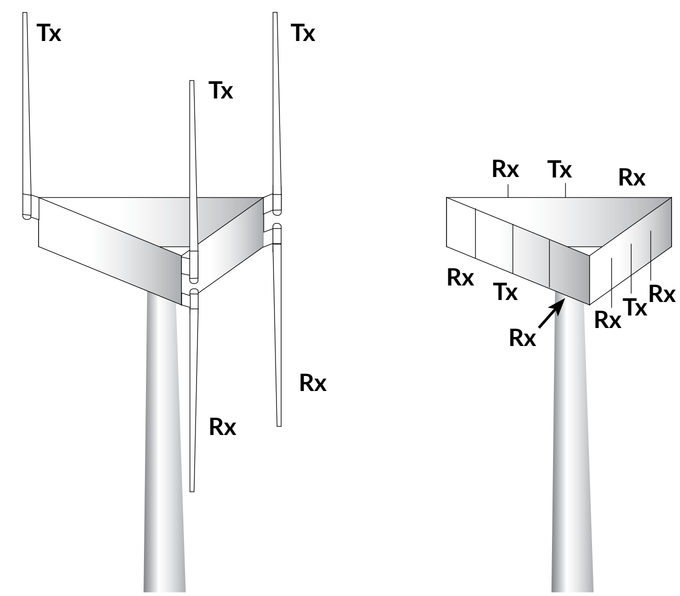
Now that you have a basic working knowledge of antennas and how specific configurations can help them perform even better—that is, by improving gain. Let's look at a much more specialized and sophisticated category: the cellular antenna.

Cellular antennas are a familiar feature in nearly every corner of the world. In many cases, these are cellular networks that bring new connectivity where it had never before been possible, and these connections depend on cellular base station antennas.

In cellular base stations, there are two basic antenna types currently in use (figure 3.11):

1. **Omnidirectional antennas,** which we defined previously as antennas that exhibit a circular radiation pattern and operate in virtually all directions, and
2. **Directional (or sector) antennas,** which operate in a specific direction, most commonly covering an arc of 120 degrees or less, depending on capacity requirements.

Figure 3.11 shows older legacy sites using vertically polarized antennas. Rural sites typically used 90° horizontal beamwidth models, suburban sites used 65° models and urban sites used models ranging from 33° to 65°. In these cases, two Rx antennas were required per sector to support Rx diversity. For modern sites, a single Dual-pol (±45° polarization) model with the appropriate horizontal beamwidth supports Rx diversity.



3.11: The two types of commonly-used cellular base station antennas

Cell reuse

What makes cellular networks different from other types of communications is the principle of cell reuse. Cell reuse is a way of increasing network capacity by "reusing," or reassigning, individual frequencies on the fly within a particular cell.

To see this process in action, consider the shape of cells and how they fit together. Typically, cells are represented as interlocking hexagons, as seen below (figure 3.12). Depending on the density of the area served, these hexagons can be miles across or cover just a few hundred feet.

As a result of this incredible flexibility, channel sensitivity is limited by external interference rather than noise issues, as older radio communications have traditionally been. The specialized pattern shaping available with directional antennas, both in azimuth (horizontal direction) and elevation (vertical space), allows incredibly precise coverage that doesn't interfere with neighboring cells.

Antenna characteristics

A cellular base station's antenna is the most critical consideration in an efficient cellular network, and it all depends on choosing the antenna with exactly the right physical characteristics for a specific application. These characteristics relate to radiation pattern, antenna gain, front-to-back ratio and a number of other critical factors.

In the real world, defining, choosing and testing these characteristics requires a great deal of technical expertise and mathematical skill, so for the purposes of this discussion, we will cover the basics with a far more generalized approach than an engineer would use in an actual evaluation.

3.12: Cell reuse in a sample map. The entire map can be covered with just 7 unique cells and still provide adequate channel isolation between cells.

Radiation pattern
The three-dimensional shape of an antenna's strongest signal transmission.

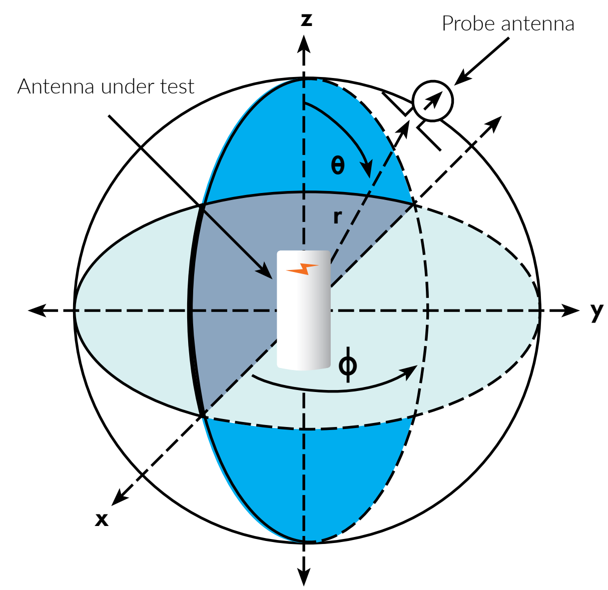
Spherical coordinate system
A geometric polar coordinate system used to mathematically map the radiation pattern of antennas.

Azimuth coordinate system
The polar coordinate system used in the field by RF engineers and surveyors to map the radiation pattern of antennas.

Radiation pattern

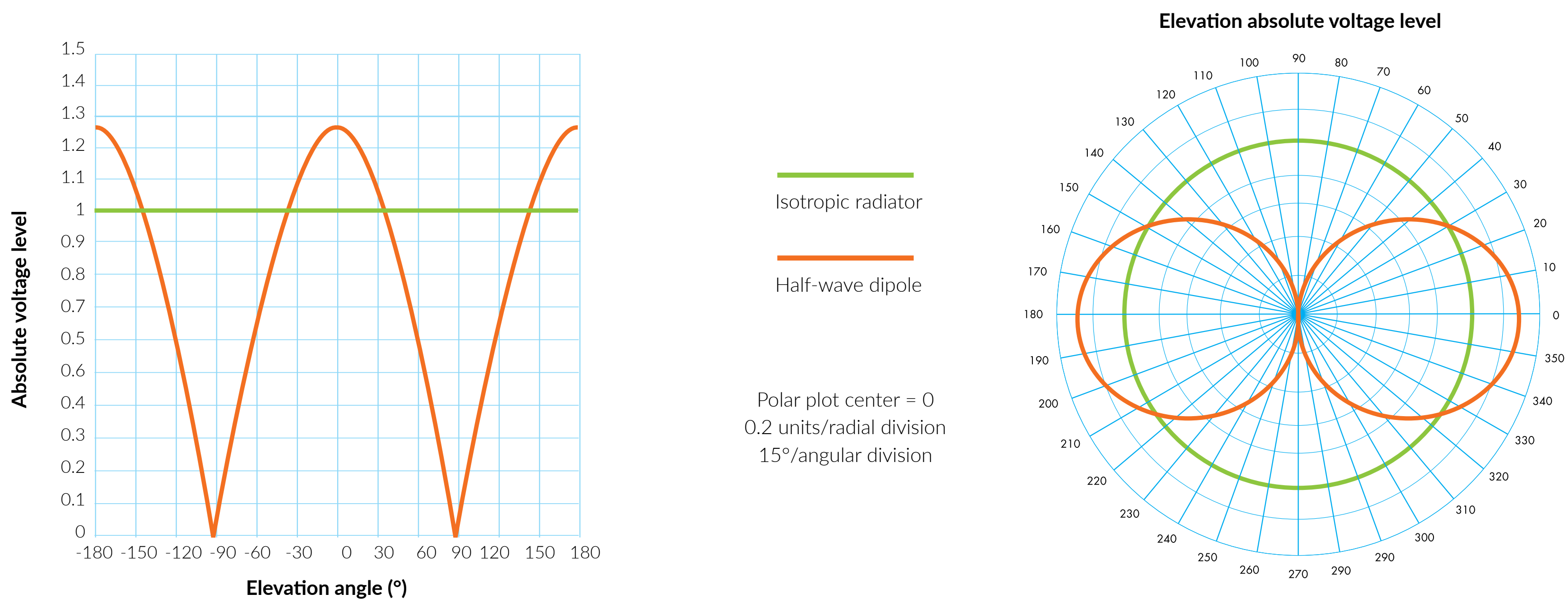
Perhaps the most obvious and important characteristic to understand is an antenna's radiation pattern. If a particular application calls for coverage in all directions, you would choose an antenna with a circular or omnidirectional radiation pattern. If your installation requires a more focused signal, a directional antenna's radiation pattern would satisfy your needs.

Mapping an antenna's radiation pattern is a fairly simple task. Connecting a probe antenna to a receiver and moving it around your tested antenna at a fixed distance allows you see the variations in signal strength. Mapping these readings with polar coordinates yields a three-dimensional map showing in which directions the antenna transmits most strongly (figure 3.13).



3.13: Moving a probe antenna around the tested antenna at a fixed distance yields a three-dimensional map of its radiation pattern

At the same time, a pattern can also be expressed as a conventional rectangular plot with angular position on the X-axis and signal strength on the Y-axis. Examples of both are shown below. Depending on the design of the antenna, the radiation pattern can display any number of shapes. The isotropic dBi reference is a theoretical "point source" and thus generates a pattern covering all directions of a sphere. As seen previously, the ½ wave dipole dBd reference pattern has nulls above and below the dipole and thus from a conservation of energy standpoint must have more gain on the horizon than the dBi reference. The absolute difference of these two standards is 2.14 dB and today most manufacturers rate their products in both dBi and dBd. Since an antenna's gain is determined by comparing it to one of these standards, the dBi rating will always be 2.14 dB greater than the dBd rating.



3.14: A system controller interface displaying voltage, amperage and alerts

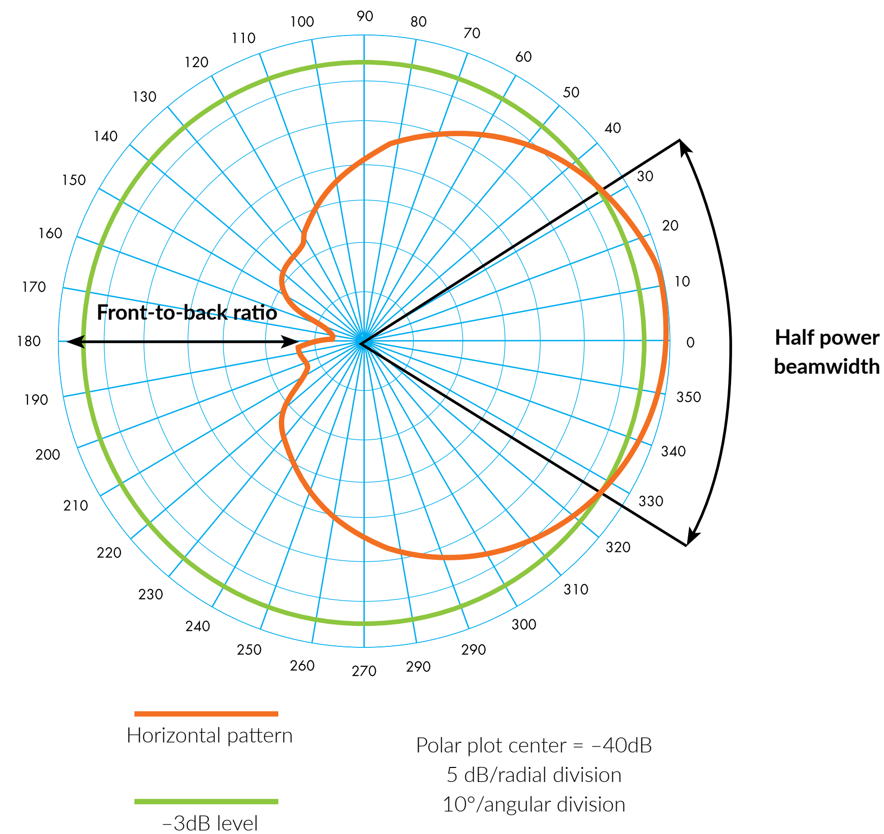
Antenna gain

As discussed earlier, an antenna's radiation pattern is directly connected to its gain, or performance power. While we cannot improve gain by increasing transmitter power without rebuilding the system entirely, we can use radiation patterns to achieve the same objective.

Gain is measured in decibels (dB) and rises as a function of increasing aperture size, which in most cases means increasing the physical size of the antenna. As a general rule, a doubling of aperture results in a doubling of gain. Though, as a practical matter, larger antennas introduce efficiency-reducing power losses that can diminish these improvements.

Front-to-back ratio

The ratio of a directional antenna's maximum directivity to "front" (where its main lobe appears) to its "back" where its reflector is located is called, appropriately, the antenna's front-to-back ratio (figure 3.17).

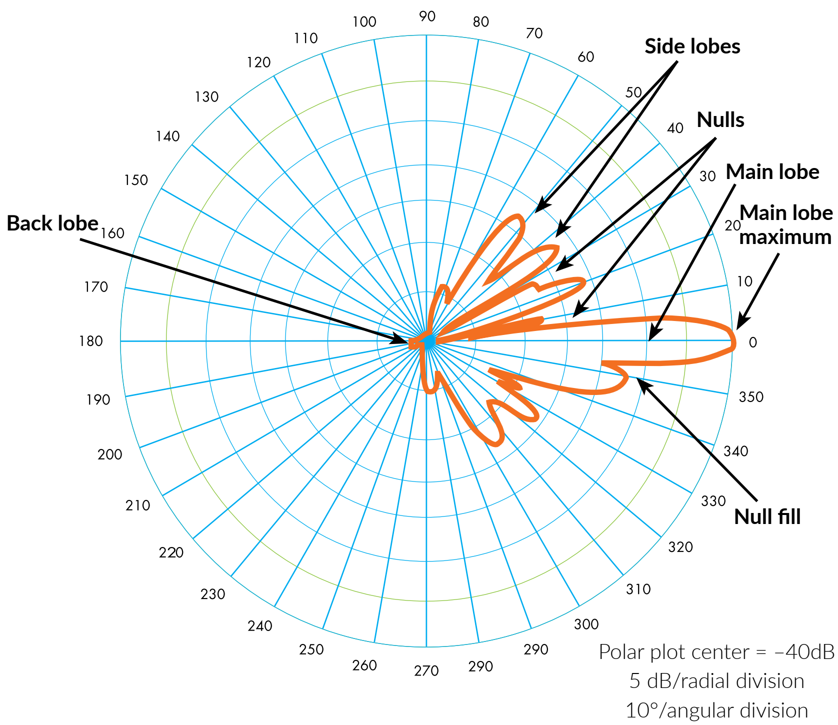


3.17: A polar representation of a directional antenna's front-to-back ratio

Side lobes and nulls

Apart from a radiation pattern's main lobe, there can also exist side lobes and nulls. Side lobes are extraneous areas of strong signal, and nulls are the low-energy spaces between them (figure 3.18). Nulls may exhibit 30 dB or more of attenuation, meaning signals found there can be as weak as one one-thousandth of the power of the main lobe.

There are ways of redirecting side lobe power back into the main lobe. This process, called null fill, can result in the widening of the main lobe and reduce gain accordingly.



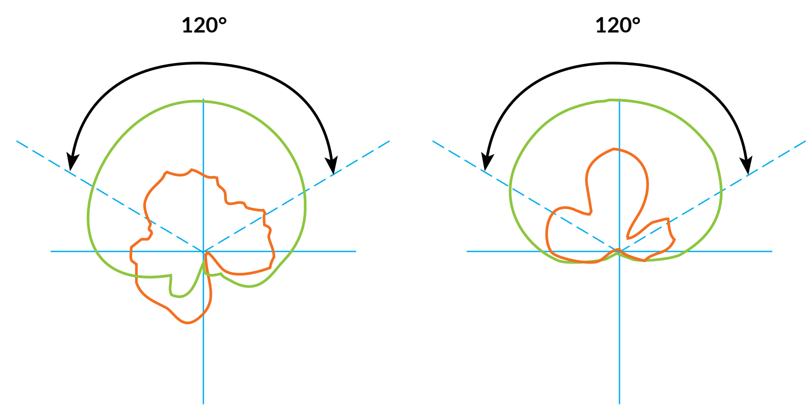
3.18: A polar representation of a vertical pattern including side lobes and nulls

Polarization

Polarization is a property of the wave produced by an antenna that describes the way that wave varies in space over time. In simpler terms, it describes the orientation of that wave, such as vertical or horizontal or slant 45 degrees (Dual-pol).

Cross-polarization ratio

This characteristic measures the performance of a dual-polarized array in distinguishing between orthogonal waves (two signals broadcast perpendicular to one another, such as horizontally and vertically). This figure is calculated as the ratio of co-polarization to cross-polarization occurring in the antenna's main lobe (figure 3.19).



3.19: Typical and directed dipole cross-polarization ratios

Sector power ratio

Basically, sector power ratio is a comparison of signal power registered outside and inside a desired receiving area as a consequence of an antenna's radiation pattern (figure 3.20). The higher the ratio, the better the antenna's interference performance.

As a practical matter, particularly in cellular network applications, lower sector power ratios indicate a higher amount of interference between antennas in adjacent coverage areas. When competing signals overlap, interference can increase and reduce performance, such as dropping a cell phone call while moving from one cell to another. Cellular networks require precise sectorized planning to prevent this kind of problem.

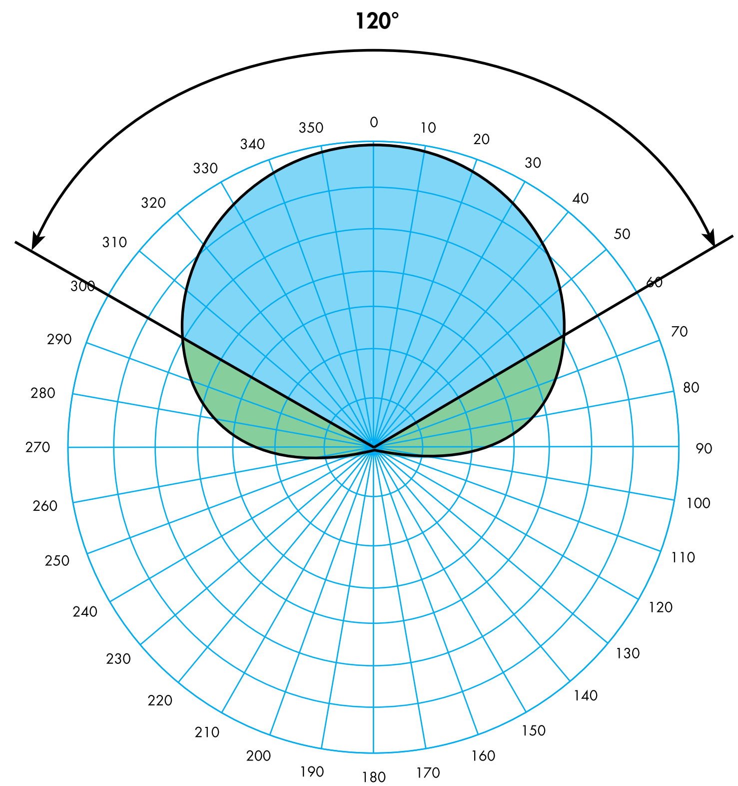
Beamtilt

As capacity requirements increase, one solution is to split the hexagons shown in figure 3.12 allowing the addition of more sites and reducing the coverage radius of the original site. To accomplish this, elevation beam downtilt is commonly used to reduce the gain on the horizon (and thus the coverage radius) as shown in figure 3.21. Mechanical downtilt results in undesirable pattern distortion on the horizon while electrical downtilt maintains the desired pattern shape.

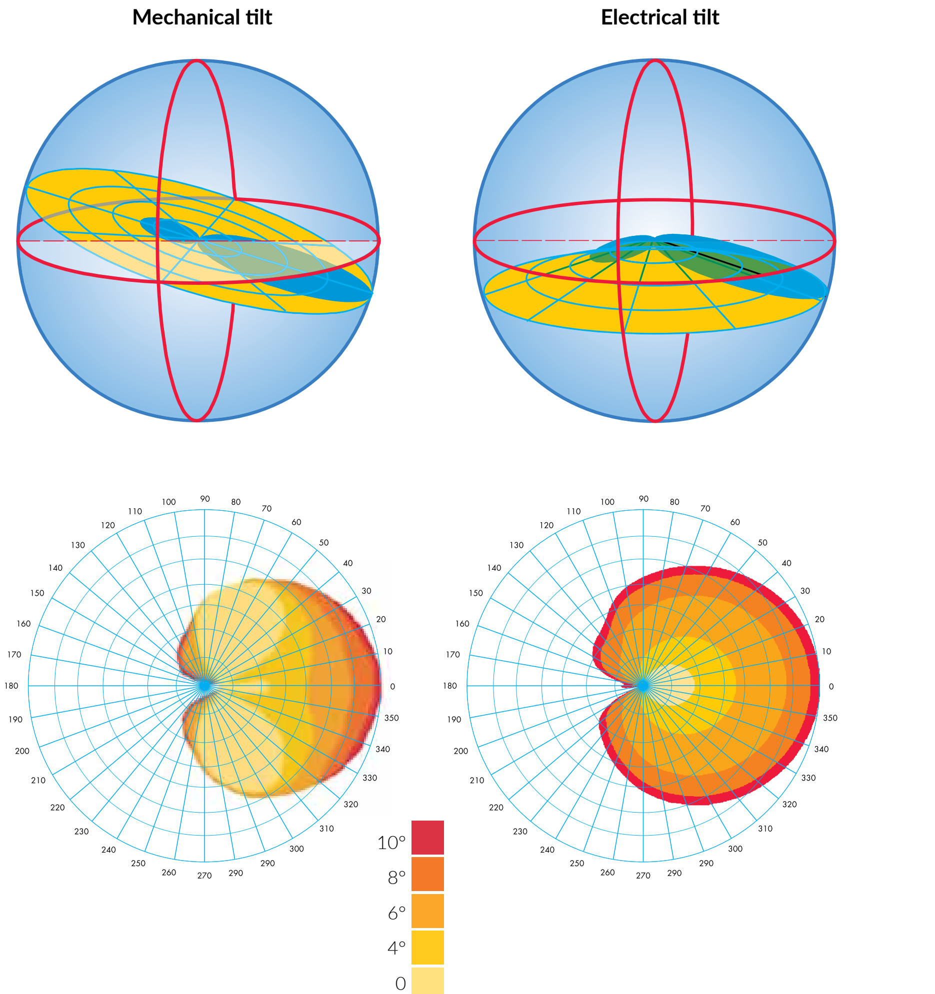
Early antennas incorporated fixed electrical downtilt, but this required multiple different models.

Cellular antennas on a practical level

When we move beyond the drawing board of theoretical antenna design to the real world, we soon discover that the laws of physics are not the only limiting factors affecting an actual installation. These issues include everything from tower weight and wind limits to local zoning board approvals for antenna size, shape, height and appearance. In most installations, compromises are necessary to satisfy all the competing interests.



3.20: Graphic and mathematical representations of an antenna's sector power ratio



3.21: Tilting the antenna changes the shape of the lobe at ground level, reducing gain

Most cellular antennas are produced in a variety of physical sizes to offer the best performance while conforming to other requirements. Chances are that you've seen cellular antennas mounted in a number of ways, featuring diverse sizes and designs, such as the commonly used lengths of 4, 6 and 8 feet.

Materials and environment

Cellular base station antennas are only as reliable as the materials that go into their construction, and the construction of their arrays. When it comes to working with the physical limitations of an antenna's location, matching the right materials to the environment is a critical consideration. Here are just a few examples.

In the antenna array itself:

- Aluminum alloys offer lightweight strength, but can be vulnerable to the elements
- Pressure cast aluminum is well suited to bases, sockets, mounts and clamps, where its hardness and resistance to corrosion are critical
- In circumstances where weight is not a serious factor, copper and brass are used for their easy plating and conductivity properties

Antenna radomes:

- High-strength, low-RF loss materials such as fiberglass offer protection from the elements
- Materials must offer UV protection to prevent deterioration due to sunlight exposure

Tower appearance:

- For purposes of appearance and zone compliance, non-metallic paint can be applied to the entire structure
- For better wear, smooth surfaces should be roughed prior to painting

These are just a few of the more obvious physical considerations. Other matters in cable selection, connector choice and termination options demand close attention as well.

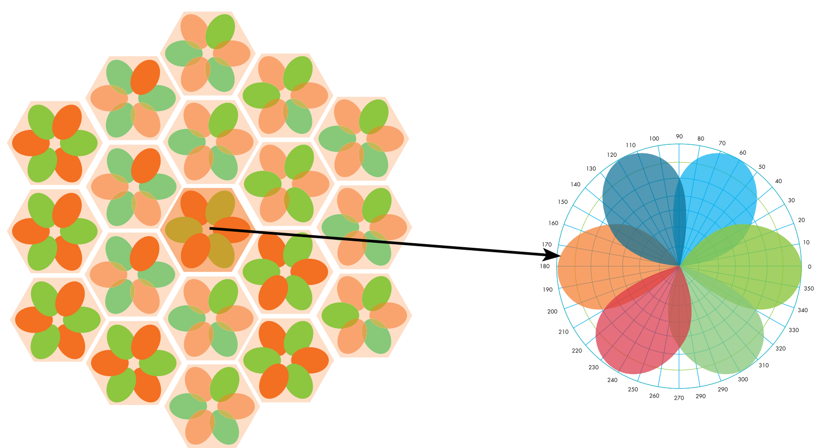
More capacity with fewer antennas

As mentioned earlier, cellular antennas are directional, often covering 120 degrees, or one-third of a complete circle. Mounted together on a triangular tower, three sets of these antennas can cover all directions. But in densely urban areas that require more capacity, narrower focus-antennas (called a six-sector scheme) can handle additional traffic along with the cost of adding more antennas. Having so many antennas in a single location makes it more likely to run afoul of local zoning codes.

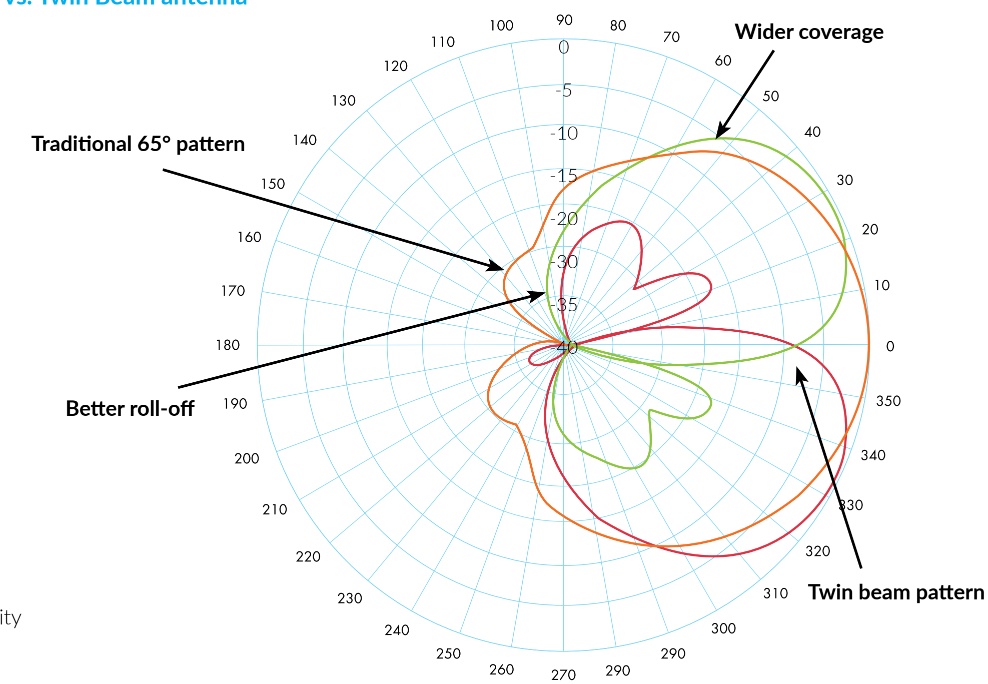
TwinBeam

One recent solution to this problem involves the TwinBeam antenna from **CommScope**, which produces two separate 35-degree beams with centers separated by 60 degrees. As the illustration below shows, this dual-lobe approach provides excellent coverage and, unlike the six-sector solution, only requires three antennas instead of six (figure 3.22).

'Six-Sector' sites



65° Antenna vs. Twin Beam antenna



Twin beam advantages

- Back-to-back broadcast channel (BCCH) re-use capability
- Enhanced RF footprint (higher gain)
- Better interference containment (better roll-off)
- Easier zoning and faster site deployment

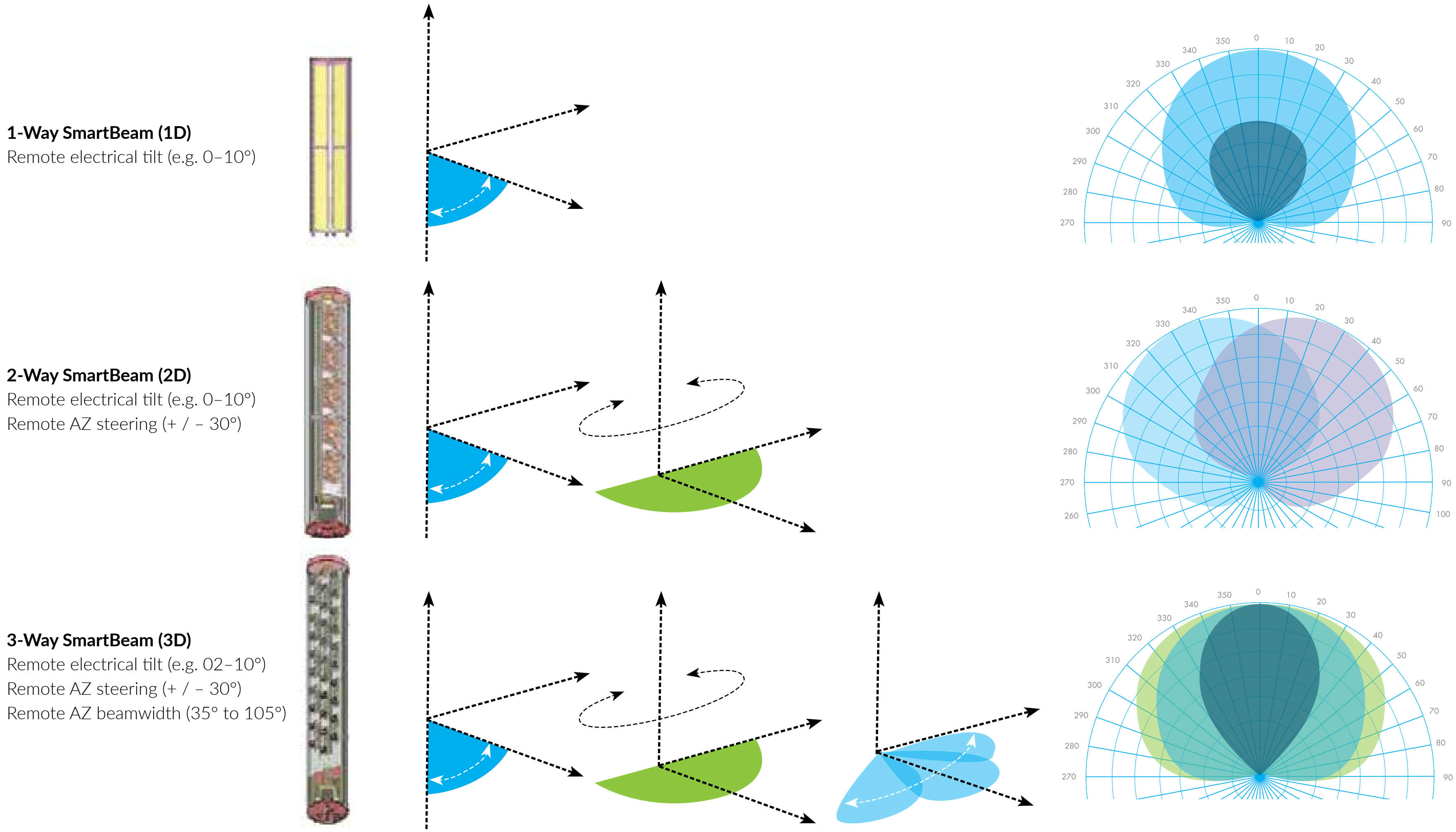
3.22: Same number of antennas, double the coverage—a six-sector pattern compared to TwinBeam installation

SmartBeam®

Another type of antenna addresses growing capacity needs by intelligently steering themselves for maximum efficiency.

The **CommScope** solution is called SmartBeam. In addition to electronic downtilt, these multiple-degree-of-freedom antennas incorporate azimuth beam steering plus or minus 30 degrees and azimuth beam adjustment from 35 to 105 degrees (figure 3.23).

SmartBeam technology video



3.23

Shannon's Law

Created by Claude Shannon and Ralph Hartley, this law establishes a theoretical limit to how much data can be reliably pushed through a given amount of bandwidth.

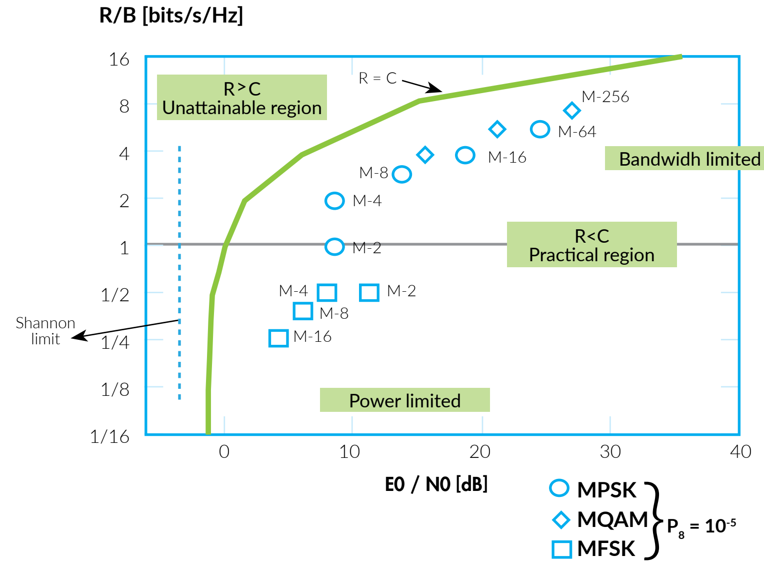
Adaptive array

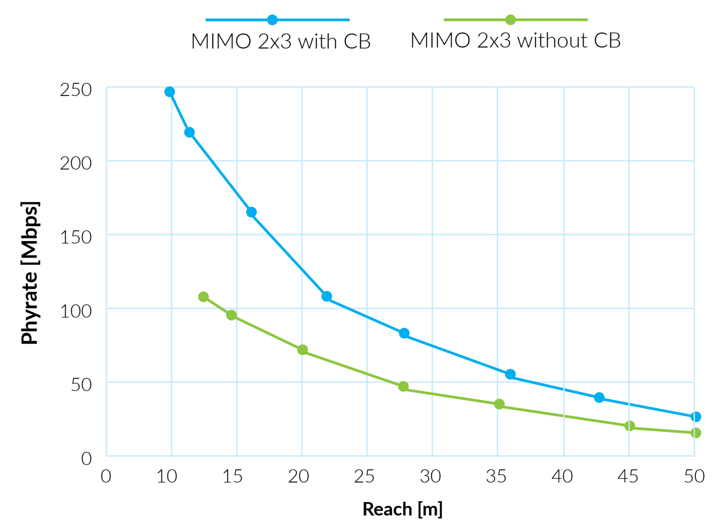
A third capacity-boosting option incorporates several vertical elements that steer a beam toward each user on a tightly managed time-division basis. In this application, each user owns a particular time slot to move his or her traffic. Of course, managing this system for a large number of users requires powerful and sophisticated digital processing, but it also holds the potential to effectively "null out" nearby interference for better high-speed throughput (figure 3.24).

The next evolution

New technologies are being developed and deployed at a dizzying rate. The current field of cutting-edge networks is collectively known as long-term evolution networks (LTE). LTE has the potential to completely reshape how networks can perform, because it incorporates a concept called multiple input, multiple output (MIMO), which splits data transmission into multiple streams and sends them at the same time on the same frequency using multiple de-correlated RF ports. The expression 2x4 MIMO means that there are 2 de-correlated paths in the downlink and 4 de-correlated paths in the uplink.

What makes this development so exciting is that MIMO offers a way around a classic limiting factor of RF communications known as Shannon's Law, which dictates how much throughput can be delivered down a given amount of bandwidth. As figure 3.24 shows you can only expect to get to within 3 dB of a bandwidth's theoretical maximum in a practical application.

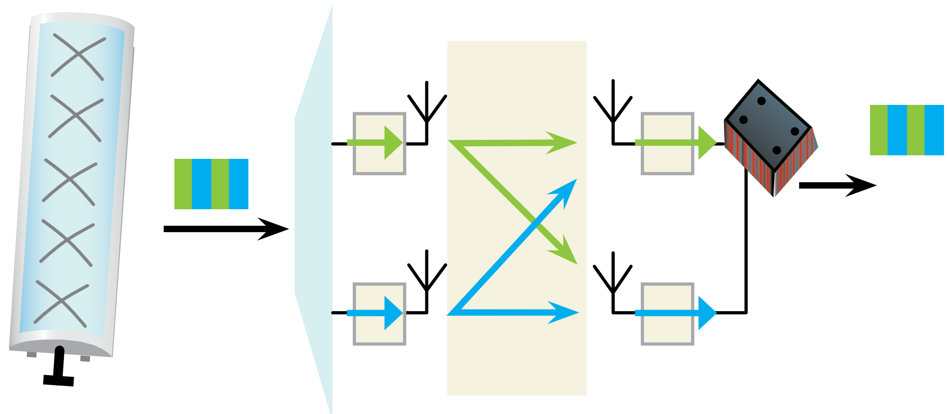




3.24: A traditional plot of Shannon's limiting law

MIMO circumvents this limit through digital signal processing (DSP), which can distinguish between the two split signal paths and reassemble them into the original data on the receiving end. This workaround literally doubles the theoretical limits defined by Shannon's Law when applied in a 2x2 MIMO configuration with two transmit and two receive antennas (figure 3.25). It is quadrupled in a 4x4 MIMO configuration with 4 transmit and 4 receive antennas. Actual throughput improvements do not quite achieve this degree of volume, but that differential is to be expected in any practical application of theoretical performance.

MIMO systems
2 x 2 SU-MIMO: Spatial multiplexing



Same time and frequency resource

- Multiple input multiple output
- Capacity gains due to multiple antennas at both ends of the link
- Multipath provides additional channel using DSP
- LTE supports 1x2, 2x2, 4x2, 4x4
- Spatial multiplexing requires a multi-path environment

Different data streams

- Space Time Block Coding is a transmit diversity mode used S/N cannot support Spatial multiplexing
- Decorrelation between antennas and propagation paths required for Spatial multiplexing
- A dual polarized BSZ for 2x2 MIMO; two separated for 4x2 or 4x4 MIMO
- Alternatively vertically polarized antennas can be used with spatial separation

3.25: This 2x2 MIMO system uses digital signal processing to circumvent theoretical throughput limits

The basics of base station antennas

Incredibly diverse and remarkably efficient, antennas are the most critical link in any communications network. Radiating radio energy into space and collecting it from space, they can connect a single network backbone or thousands of individual users.

By virtue of their design, antennas can cover virtually any desired area of any shape. But it takes a lot of insight, knowledge and planning to get the most out of every watt. It all comes down to understanding your application's needs and its limitations.

With your new understanding of how antennas work, and how their performance is measured and compared, you may think twice the next time you are searching for more "bars" on your cell phone or a faster Wi-Fi connection for your computer. Then look up at the next TV aerial or cell phone tower you see and remember the complexity of the invisible processes that make modern communications possible at home, at work and on the go around the world everyday.

Chapter 3 summary

Antennas:

- Structures that radiate and receive radio energy
- Can achieve 80 percent efficiency or greater
- Directional (sectorized) or omnidirectional

Performance characteristics:

- Radiation pattern
- Polarization
- Gain
- Aperture

Enhancements through design:

- Vertical stacking
- Element spacing
- Horizontal pattern shaping
- Downtilt

Cellular base station antennas:

- Sectorized, grouped antennas commonly covering 120 degrees or less
- MIMO and LTE technology represent next step in speed and reliability

Working within the limits:

Co-siting solutions

If you've ever tried to get more use out of the space in your home by combining a home office with a guest bedroom, you may not have been entirely satisfied with the results. Sure, you've saved space by making one room do the job of two, but you probably found that it can't do either job quite as well as a dedicated space would have allowed.

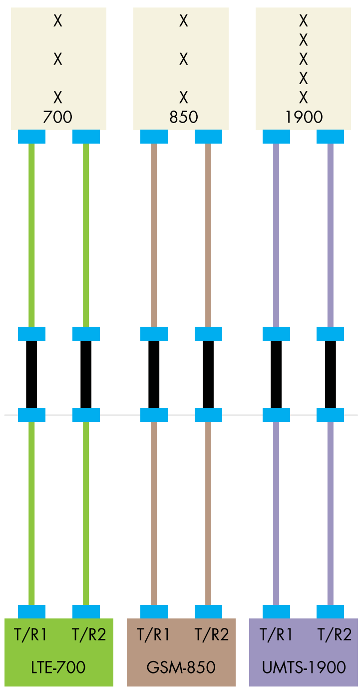
This tradeoff of space for utility is also the guiding principle behind co-siting a cellular installation. With space at a premium, there are real incentives to reducing your equipment footprint but every square foot saved places new constraints on the way that base station operates. Since every site has unique limitations, it can be a challenge to identify and implement the best *co-siting solutions*.

Whatever the specifics of a given cellular installation may be, **CommScope** offers a wide range of solutions that meet virtually any installation requirement. It takes a combination of technology and insight to make the best of every situation.

Co-siting solutions
The technology and techniques that allow cellular base stations and air interfaces to share architecture and operate within limiting factors of their locations.

Dealing with the realities

Just as it would be ideal to have an unlimited number of rooms in your home for every possible purpose, it would be ideal for cellular base stations to be equipped with their own dedicated antennas and feeders at every cell site (figure 4.1).



4.1: Multiband sector with separate feeders

If such an arrangement were possible in every installation, the benefits could include:

- Individually optimized antenna pattern, azimuth direction and downtilt angle
- Minimal RF path loss and signal mismatch
- Reduced interference and intermodulation between systems
- The ability to perform maintenance on one system without impacting the others

Sadly, this arrangement isn't a practical option for most real-world designs. When a cellular base station makes the move from the drawing board to the tower installation, its design becomes subject to an incredible number of variables and limiting factors. Some of the more common limits are:

- Local zoning ordinances that restrict quantity, size and location of antennas
- The tower's structural weight limits and wind load restrictions
- Budget constraints that limit both the initial and ongoing costs
- Scheduling demands that require accelerated service rollouts

Making the most of every watt

To address these limits and wring greater performance from every watt of power, co-siting solutions can help different technologies operate on a single architecture. Even networks operated by competing companies can realize mutual benefits by sharing site equipment, much as competing airlines will honor each other's tickets in the event of flight cancellations. In fact, such sharing agreements are now the norm with consumers benefiting from the providers' reduced operational costs in the form of better transmission speeds and reduced cell phone and data bills.

Co-siting solutions are usually based on specific equipment and configurations designed to improve performance within a defined set of circumstances under a defined set of limitations.

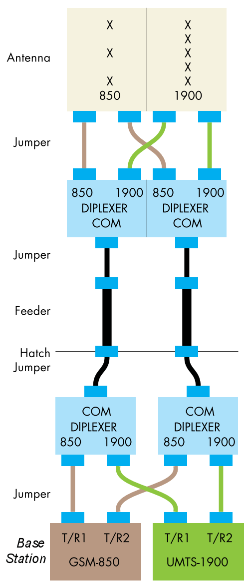
Multi-band combining

One frequently used technique is called *multi-band combining*, a method of frequency multiplexing. It takes advantage of the fact that feeder cables are naturally well suited to being shared by multiple frequency bands. In other words, multiple base station services can be funneled into a single feeder cable that runs up the tower to the antennas. Those services can then be split away from that one cable directly beneath the antennas.

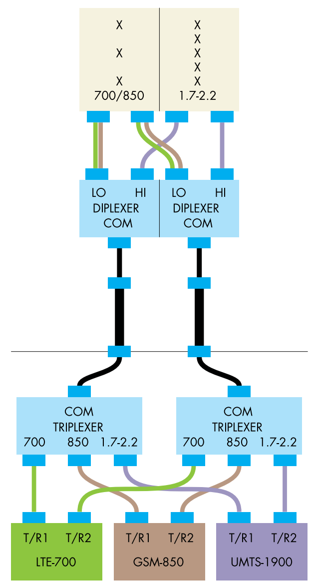
To visualize this concept, think of how you bundle your home or office computer's wires into a single plastic cable wrap; at one end, the cables separate into various ports on the back of your computer. On the other end, the cables separate into your keyboard, mouse, network and printer connections.

To achieve the benefits of frequency multiplexing, the feeder cable must be equipped with the correct combining devices. Two or more frequency bands can be combined using multi-band combiners. Multi-band combiners are often added to a system as separate components, but they can also be built directly into other components such as antennas.

Widely known as crossband couplers, these combiners may be referred to as diplexers (two frequencies), triplexers (three frequencies), and so forth according to the number of frequency paths involved (figures 4.2 and 4.3).



4.2: Shared feeders using diplex crossband couplers



4.3: Shared feeders using triplex crossband couplers, with broadband antennas using diplex crossband couplers

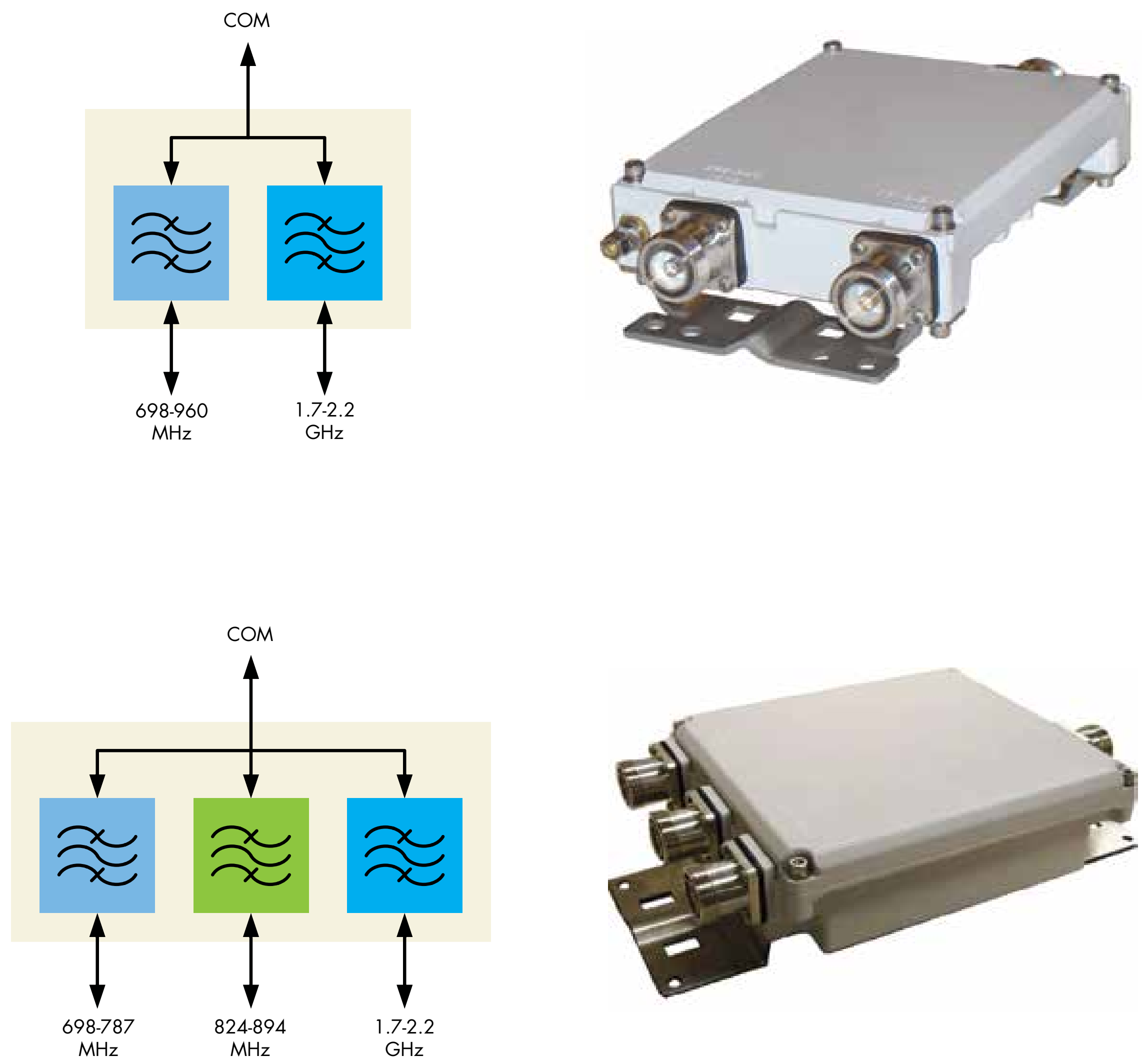
Multi-band combining
A configuration that connects multiple base station services that operate in separate bands to multiple antennas via a single feeder cable and its associated couplers.

The kind of crossband couplers required in a particular application is largely determined by the frequencies the system uses, and, more specifically, how far apart from each other those frequencies are. In systems with wide frequency separation such as 700-1000 MHz, 1700-2200 MHz and 2400-2700 MHz the needed crossband couplers are likely to be low-cost, compact devices that introduce virtually no loss or mismatch.

However, when dealing with frequencies that are relatively close to one another, such as 700 MHz and 850 MHz, the appropriate crossband coupler grows more complex, bulky and expensive (figure 4.4).

On the antenna side of the connection, additional efficiencies can be gained among broadband antennas that can accept more than one frequency through a single port. This allows it to operate over a range of bands through one feeder cable, as shown in figure 4.3.

Like the other circumstances involved in planning an efficient and compliant base station site, antenna selection and the base stations' assigned frequencies can play a large part in how a particular co-siting solution comes together.



4.4: Compact diplex and triplex crossband couplers, with example frequency differentiation

Same-band combining

In some instances, multiple services require the use of the same frequency band. When this happens, regular crossband couplers, which are designed to suit specific frequency separation, don't provide the solution we need. Instead, we can use a variety of *same-band combining (SBC)* options, which can allow different services to share the same space on the electromagnetic spectrum.

In some applications, same-band combining is even used for single-service systems—not to allow other services, but to increase the channels available to the one operating service. In all cases, the idea is to combine transmit signals (TX) and divide receive signals (RX). The best way to achieve this depends on the specifics of the application.

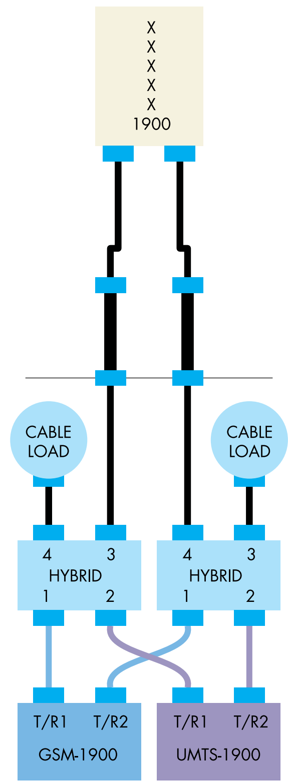
Now let's look at some of the more commonly used techniques.

Hybrid combining

Hybrid combiners offer a low-cost means of combining TX signals and dividing RX signals (figure 4.5), but this advantage comes at the cost of other operational restrictions inherent in its design.

The main disadvantage of this technique is the high rate of loss experienced in both directions. This loss increases with the number of ports involved, so hybrid combiners are generally used only in two-port applications.

Another consideration is the significant heat it generates which must be dissipated, adding costs and creating even more design limitations. These drawbacks limit the practicality of hybrid combining to in-building coverage and similar uses. It is rarely used in cellular sites.



4.5: A hybrid combiner, using cable load to lower passive intermodulation

Same-band combining (SBC)
A base station configuration that allows multiple services to share the same bands.

Guard bands
Narrow gaps inserted into the bandwidths managed by the LLC to distinguish different signals riding on the same bands.

Low loss combiner-multiplexer

The low loss combiner (LLC) offers a different way to combine base station transmitters. Commonly employed for combining TX signals, integrating a duplexer allows for distribution of RX signals as well (figure 4.6).

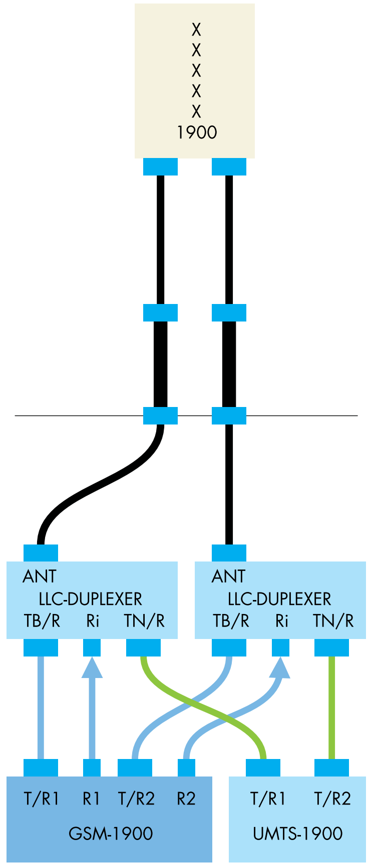
Like crossband couplers discussed earlier, the LLC is a filter multiplexer. However, unlike a crossband coupler that requires spaces between bands—you'll recall that the bigger the spaces, the better the coupler operates—the LLC handles frequencies inside the same bandwidth.

This is possible due to the addition of guard bands, which act as very small gaps within the band. They create boundary spaces between the frequencies, allowing them to be distinguished from one another.

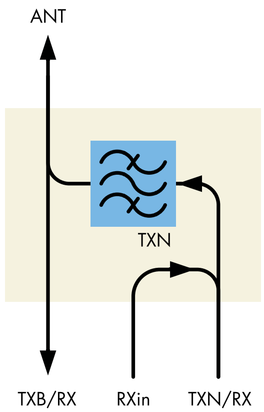
Including these tiny *guard bands* often requires those narrow frequencies to be left unused, which adds up to slight bandwidth loss. In LLC design, smaller guard bands incur greater cost, size and complexity, so an economical alternative is to re-use the "lost" guard band space with a second feeder and antenna.

LLC design significantly reduces insertion loss over that of a hybrid combiner, but its reliance on filter multiplexing places significant restrictions on its scalability. As technology develops, networks require constant upgrading, adjusting and scaling which often means the adjustment or replacement of the LLC component. Recent developments in remotely tuned LLC hardware have helped reduce this limitation, but it remains a significant drawback for many applications.

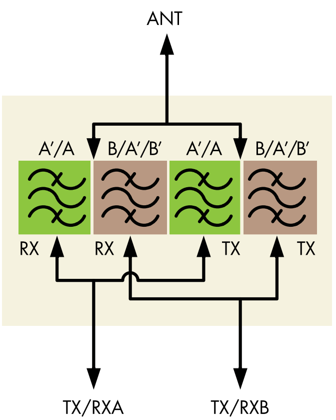
Several examples of LLC realizations are shown in figures 4.7 and 4.8.



4.6: An LLC with integrated duplexer; RX distribution from GSM BTS



4.7: An LLC combines a narrow portion of TX band into broadband path; includes duplexer for RX re-injection



4.8: Filter multiplexer for downlink and uplink—a quadruplexer

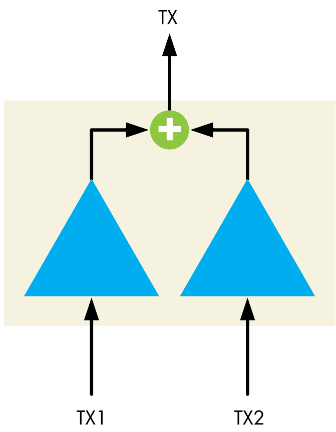
Amplification

Another technology that makes co-siting possible is amplification. There are several ways amplification can be used in support of the devices listed above, expanding their utility, power and range.

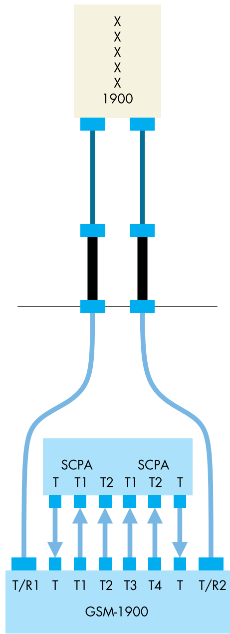
Single carrier power amplifier. You will recall that one of the hybrid combiner's drawbacks was its high rate of insertion loss for both TX and RX signals. One way to compensate for this is to add a single carrier power amplifier (SCPA) (figure 4.9).

The SCPA is highly efficient in regard to power consumption, but is only suited to certain engineering standards, such as the Global System for Mobile Communications (GSM) established by the European Telecommunications Standards Institute (ETSI). Still, in those applications where the SCPA is appropriate, the SCPA offers a low-cost means of improving hybrid combiner performance (figure 4.10).

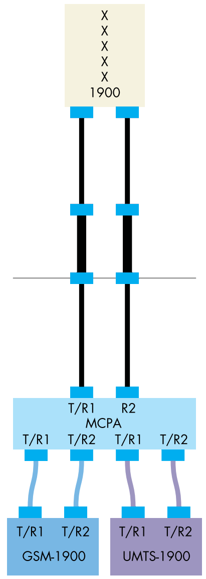
Multi-carrier power amplifier. Like the SCPA, the multi-carrier power amplifier (MCPA) is a high-power amplifier for carrier signals. Unlike the SCPA, however, the MCPA can also combine multiple RF signals into a single output. Its input circuits can be expanded to accommodate from two to eight ports, and sometimes even more (figure 4.11).



4.9: An SCPA module amplifies and combines two transmitters into one path



4.10: An SCPA installed between radios and BTS duplexer



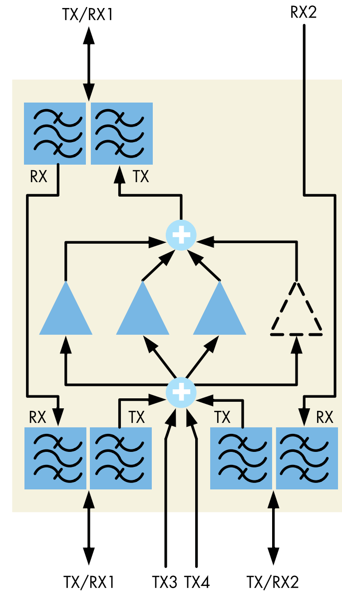
4.11: An MCPA with integrated RX distribution

The MCPA's strong suit is boosting transmit power to increase the coverage or capacity of a particular base station. It also offers complete frequency agility, allowing free use of all frequencies within a license band. This makes it a very easy system to interface to other technologies. Its design generally incorporates one or more amplifier "bricks" working in parallel to provide the necessary power (figures 4.12 and 4.13).

An MCPA's demanding power consumption is its most notable drawback, which leads to elevated implementation and operational costs.

Receiver multicoupler. As its name implies, the receiver multicoupler (RXMC) distributes RX signals from shared antennas to multiple receivers. By splitting the signal this way, a natural side effect is some loss of power. To compensate, the RX input first crosses a low-noise amplifier (LNA) which preserves signal strength, preceded by a preselector filter. Inclusion of an LNA is recommended for most applications with more than two receivers.

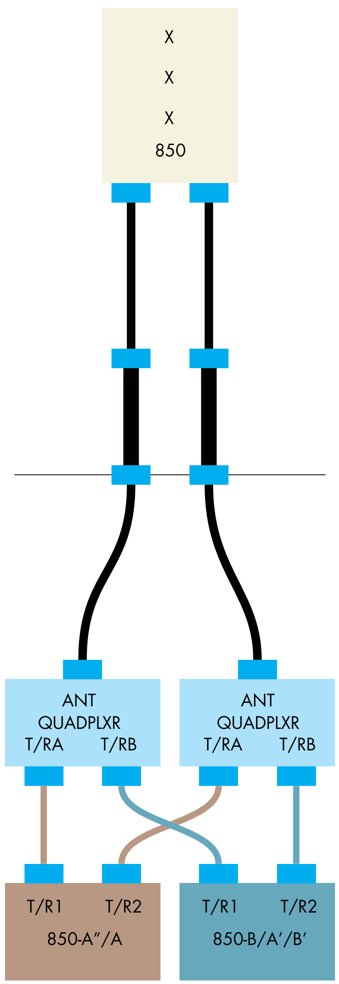
As a rule, the RXMC distributes the full RX frequency band to all outputs with the same degree of gain across the board. To individualize distributions, the RXMC may allocate specific signal strength to each receiver by unequally dividing the gain. This is a useful option when dealing with different locations, or with a receiver that will further divide its signal to other receivers down the line.



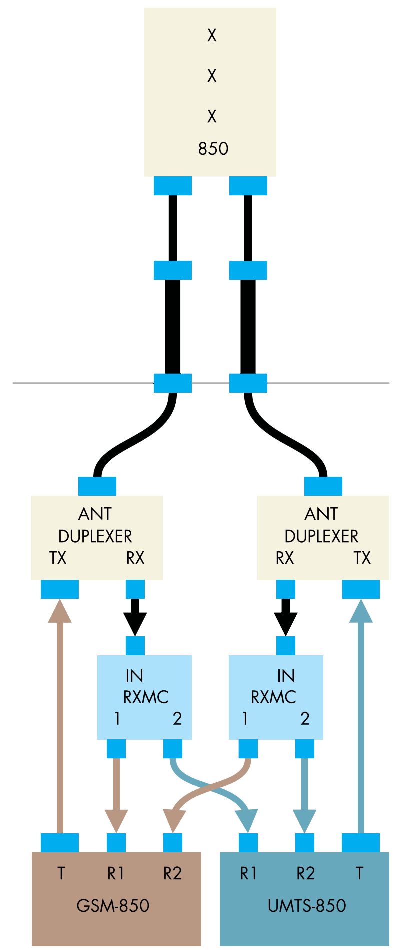
4.12: An MCPA for one sector with two duplexed inputs and two simplex inputs; three amplifier bricks are working in parallel

4.13: An MCPA for three sectors, two duplexed inputs and six simplex inputs per sector, one amplifier brick per sector, plus one hot standby brick

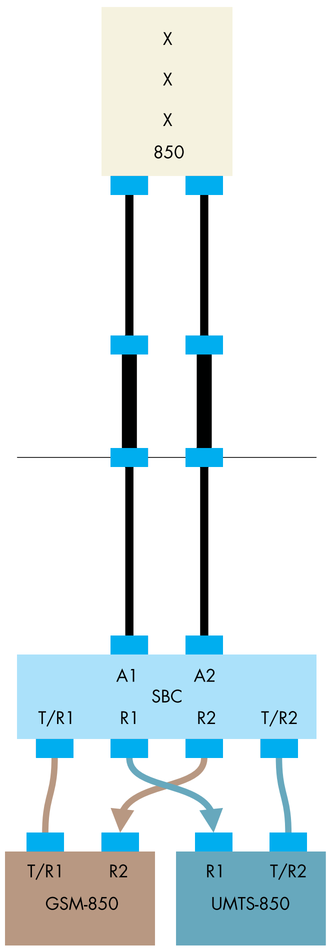
Other integrated configurations. The following figures illustrate other same-band combining technologies (figures 4.14 through 4.18).



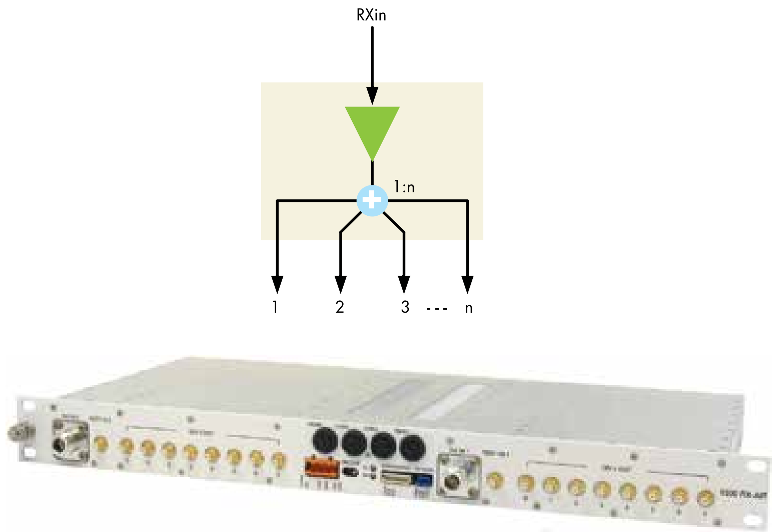
4.14: Antenna sharing accomplished with a TX/RX quadruplexer



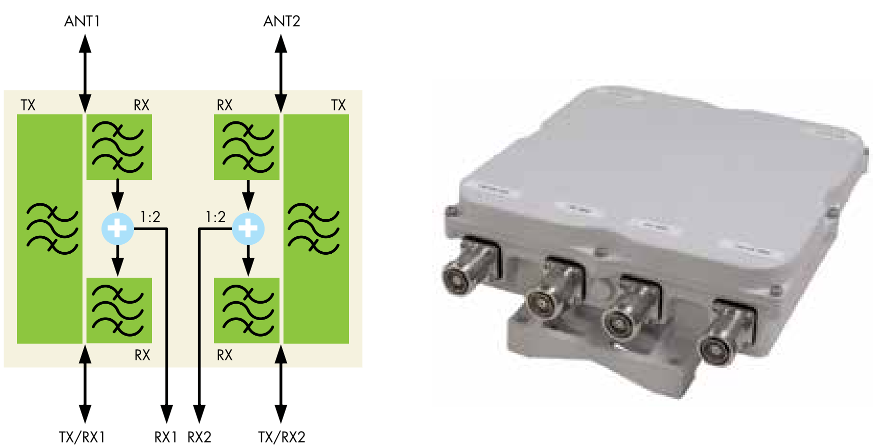
4.15: RX distribution to simplex BTS using duplexers and RXMC



4.16: Antenna sharing accomplished with integrated Duplex/RX SBC



4.17: Dual RXMC with eight outputs per channel



4.18: Integrated SBC

Tower-mounted amplifiers. Working with these other co-siting solutions, a tower-mounted amplifier (TMA) improves the base station's sensitivity the same way a hearing aid can improve diminished hearing. It works to offset the losses experienced by RX signals as they travel to the receiver. This improvement in signal clarity is seen in the carrier-to-noise ratio (C/N), measured in decibels (dB). Adding a TMA to the RX circuit on a cellular base station can yield a typical improvement of 5-6 dB.

TMAs are a key part of RF path technology. Properly implemented and configured, they improve:

Coverage. They boost the effective service radius of a cell base station while improving signals in weak spots, such as indoors.

Accessibility. They significantly reduce failed access attempts.

Retainability. They improve a site's retainability, or its ability to maintain connections within and across cells for fewer dropped calls.

Co-channel interference. They improve call capacity in spread spectrum systems.

Data throughput. They enable higher order modulations for increased traffic capacity.

Handset battery life. Because less power is required from the cell phone's transmitter, TMAs prevent unnecessary battery drain.

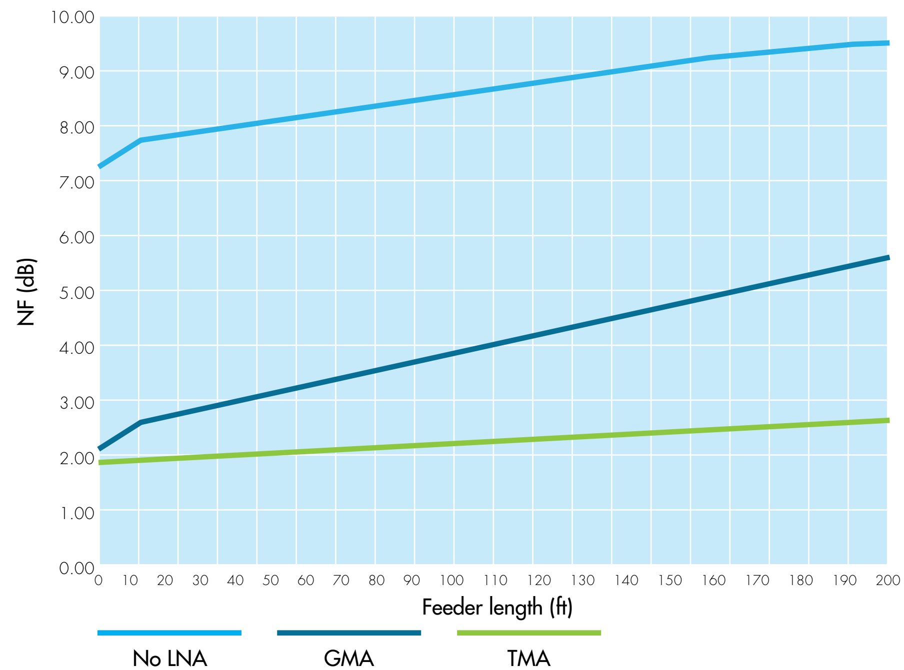
With the right adjustments, TMAs offer all these advantages that help operators enhance their network capacity and coverage.

TMA benefits

To gain the maximum advantage, it is important to boost the RX signal level before it becomes degraded by feeder loss between the tower and the base station receiver. This is the reason the TMA should be mounted at the tower top, as close to the RX antenna as possible.

An LNA may also be installed at the ground level and is then called a ground-mounted amplifier (GMA). When it reaches the GMA, the RX signal will already be weaker and noisier than it originally was at the antenna. Therefore, the sensitivity improvement a GMA can provide is limited at it's improving an already weakened signal. On the other hand, its main advantage is that it is easier to install than a TMA, and does not occupy precious tower space. Because it doesn't introduce the size and weight concerns of a tower-mounted TMA, the GMA design can focus on performance. Superconductors and cryogenic cooling can be used to maximize performance and partially offset the disadvantage of its ground-level location.

Many factors contribute to feeder loss. Smaller cable diameter, longer feeder runs, and higher operating frequency all influence performance, and the TMA offers a single method of offsetting all these factors with one remedial measure. You can see how TMA and GMA implementations affect the noise levels in a system in figure 4.19.



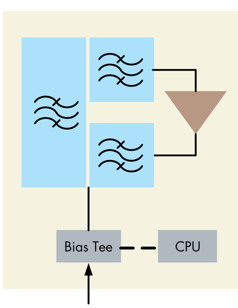
4.19: Noise figure in a system with no LNA, with a GMA and with a TMA; the superior performance of the TMA is evident in its lowest noise figure

TMA configurations

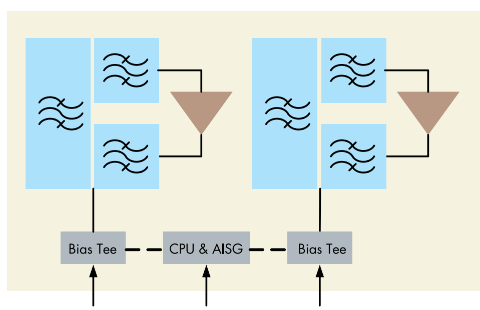
As explained in our earlier look at the receiver multicoupler (RXMC), a tower-mounted amplifier employs an LNA (with a preselector filter) to boost signal strength to compensate for division loss. Since modern TMAs often employ a dual duplex configuration, which allows the use of duplexed feeders, two additional filters are needed to pass the signals between the BTS and antenna.

Dual-band TMAs are essentially a pair of single-band TMAs integrated into one device. Some types feature separate RF paths for each band, while others diplex the bands into a single path at the BTS port or at the ANT port. Interestingly, diplexers can also be integrated into single-band TMAs to offer an additional, non-amplified path. These devices are called *bypass or pass-through configurations*.

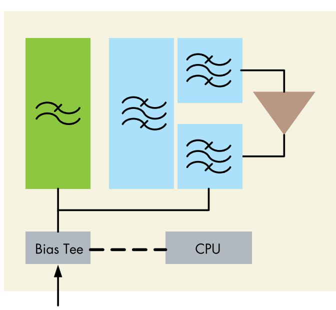
As a result of growing demand for reliable cellular network service, coupled with frequent restrictions on the amount of equipment permitted on a particular cell site, dual-band TMAs are becoming more and more popular as a co-siting solution. You can see examples of some different TMA architectures in figures 4.20 through 4.26 beginning on this page and continuing on page 14.



4.20: Single-band TMA



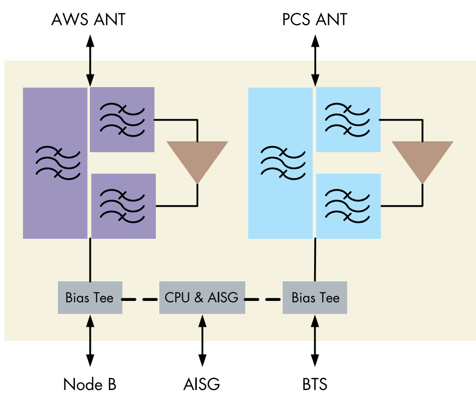
4.21: Twin single-band TMA with AISG support



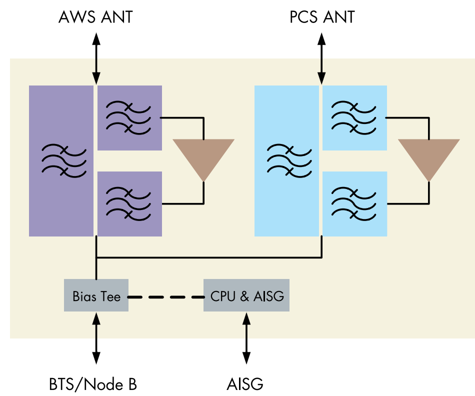
4.22: TMA with integrated diplexer, bypass path

Bypass or pass-through configuration

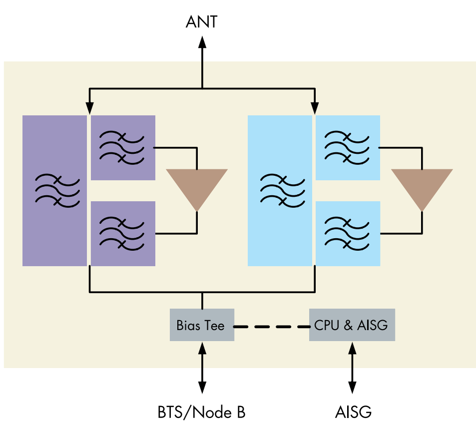
A single-band tower-mounted antenna with an integrated diplexer that adds a secondary, non-amplified RF path to the system.



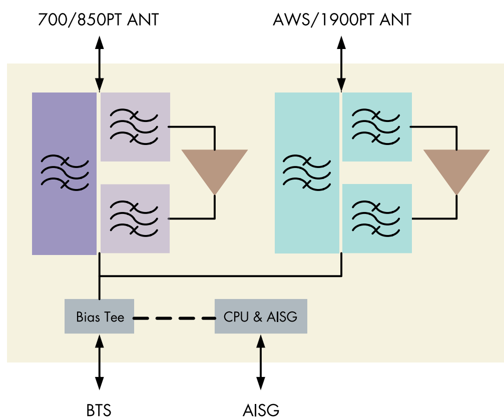
4.23: Dual-band TMA with AISG support



4.24: Diplexed dual-band TMA with AISG support



4.25: Dual diplexed dual-band TMA with AISG



4.26: Diplexed dual-band TMA with pass-through and AISG

Enhanced features: AISG

The *Antenna Interface Standards Group (AISG)* is comprised of representatives from the world's leading wireless equipment manufacturers and service providers, including **CommScope.** AISG's standards have led to improvements in remote control and monitoring of antenna downtilt, TMA alarms, and other important advances. Adoption of these protocols has advanced performance and assured interoperability between various systems—a major boon for co-siting solutions like the ones discussed above.

Contemporary co-siting components must accommodate AISG communication, whether they process the signals or simply pass them along to other devices. The AISG protocol currently includes procedures for monitoring and controlling TMAs, such as setting gain and reporting alarms. Additional procedures may be defined in the future to support a wider range of "smart" co-siting devices that will help optimize performance, enable remote supervision of the RF path, and reduce cost of ownership.

Antenna Interface Standards Group (AISG)
Founded in 2001, the AISG represents more than 40 top manufacturers and service providers from all over the world. AISG publishes universally accepted industry protocols for communications between base stations and tower-based equipment, such as antennas and TMAs.

Making the most of available space and power

The design of a cellular communications system reflects many choices and compromises. The result is that no two are exactly alike. Certain preferred characteristics come at the expense of other characteristics; those choices are always made with an eye toward conserving space, reducing costs and operating within constraints.

By employing the kind of innovative solutions discussed in this chapter, wireless operators are able to improve service and reduce costs by working together to share infrastructure wherever possible. We see the benefits in the form of lower cell phone bills, clearer and more reliable calls, and faster data downloads and Web surfing on our mobile devices.

Chapter 4 summary

Co-siting solutions:

- The technology and techniques that allow more performance in less space
- Driven by limits on amount, weight and cost of base and antenna-mounted equipment

Multi-band combining:

- Leverages feeder cable's capacity for multiple frequencies
- Requires frequencies in separated bands
- Uses crossband couplers in diplex, triplex or more complex configurations

Same-band combining:

- Hybrid combining: inexpensive but lossy
- Low loss combiner: efficient but constrained frequency applicability

Amplification:

- Single carrier power amplifier: low cost, high efficiency, limited applications
- Multi-carrier power amplifier: scalable, flexible but expensive to install and operate
- Tower-mounted amplifiers: broad-based receiver performance boost

Chapter 5

Talking and listening at the same time:
Transmission and receiving isolation systems

Right now, millions of people around the world are downloading music, surfing the web, texting, talking and listening on their mobile devices. It's probably safe to say that they are *not* thinking about the science or technology that enables every download, text or conversation. Mobile devices are simply a way of life.

Here at **CommScope,** we're continually fascinated by the technical innovation and principles behind wireless communication. Take transmission and receiving isolation systems, for example. Unlike conventional landline phones, cell phones are actually radio receivers and transmitters, so maintaining simultaneous two-way communication—talking and listening during a call—is more complex than it appears.

Duplex communications
A transmitter and receiver that work at the same time on the same RF device.

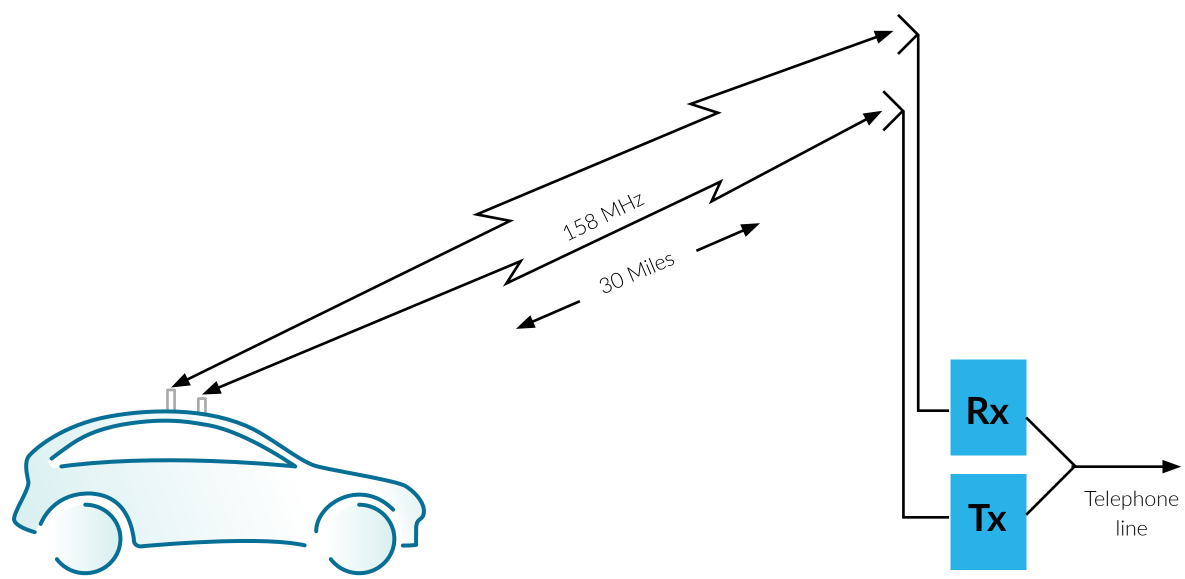
Isolation
The amount of separation achieved between the transmitter and receiver in a duplex communication system. In general, more isolation translates to less interference and clearer communications.

An RF communications system that employs this simultaneous, two-way flow of voice, data or other information is called a *duplex system*. Duplex communications systems combine multiple transmit and receive channels on a shared antenna, with information flowing both ways at the same time.

Imagine the simultaneous flow of traffic on a busy two-way street. You immediately see the importance of keeping the two different directions of traffic separated. Just as vehicles on a busy, two-way street require clear lane markings to avoid collisions with oncoming vehicles, duplex RF channels also must be "isolated" from each other to avoid interference.

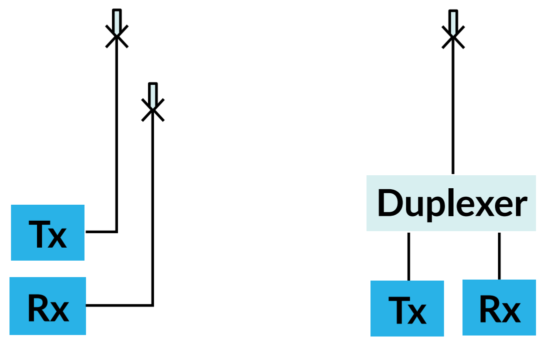
In RF terms, *isolation* is measured as the loss between two channel ports, either transmitter-to-transmitter or transmitter-to-receiver ports. The higher the loss, or isolation, between the two ports, the cleaner the signal.

To illustrate this concept, think about making a cell phone call from your car. This simplest of duplex systems—one transmitter and receiver pair communicating with another transmitter and receiver pair—requires that both the phone and receiving station be able to receive and transmit at the same time, allowing a normal telephone conversation to take place (figure 5.1).



5.1: Duplex operation between two pairs of transmitters and receivers

To allow this communication to flow on a single antenna, a *duplexer* must be used with adequate isolation measures (figure 5.2). Measured in dB, isolation is a critical consideration in the design of any duplex system. Without proper isolation, a transmitter will adversely affect the performance of its associated receiver, even though they may operate on different frequencies.



5.2: Two solutions: Use two antennas, or a single antenna with a duplexer

The specifications covering a particular receiver, for instance, may indicate that any RF signal outside the receiver's passband (which can be as narrow as 15 kHz) will be attenuated, or weakened, by as much as 100 dB. That means that the transmission's power will be reduced to 1/10,000,000,000th of its original strength, making the communication unintelligible and useless in most cases.

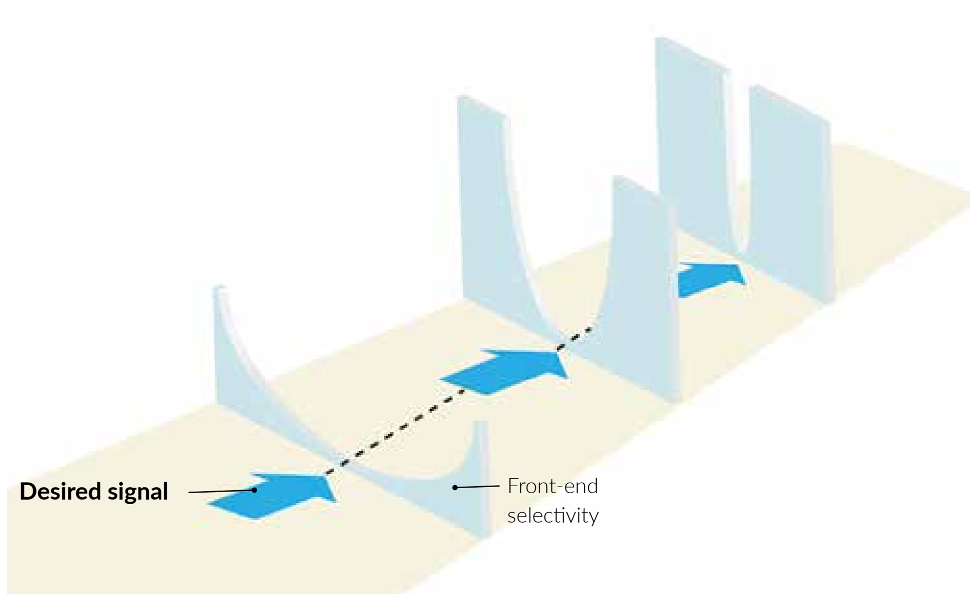
You might think that such a selective receiver would prevent interference from a transmitter operating on a frequency far outside the receiver's passband. After all, if the interfering signal is 5 MHz away, how could it create complications when just being 5 kHz off the mark reduces the transmitter's signal to virtually nothing? The answer lies in the characteristics of modern receivers, and the way they can step high-frequency signals downward to achieve such precise frequency selectivity.

Duplexer
A device situated between a duplexed antenna and its associated transmitter and receiver. A duplexer's function is to provide isolation between the signals.

Receiver desensitization
Interference caused by unwanted frequencies entering a receiver's upper-stage passbands. These errant signals create electrical variances that impede the receiver's operation.

The first challenge: receiver desensitization

Receiver desensitization is an inherent side effect of modern receiver design, which receives relatively high-frequency signals (often between 700 MHz and 3500 MHz). These signals pass through frequency-lowering stages in the receivers, which allow the receivers to feature such narrow, selective passbands (figure 5.3). Once the signal has been lowered enough, only a small band remains and the circuitry can reject other bands within a margin measured in dB. A receiver's specification sheet will include this measurement of overall selectivity.

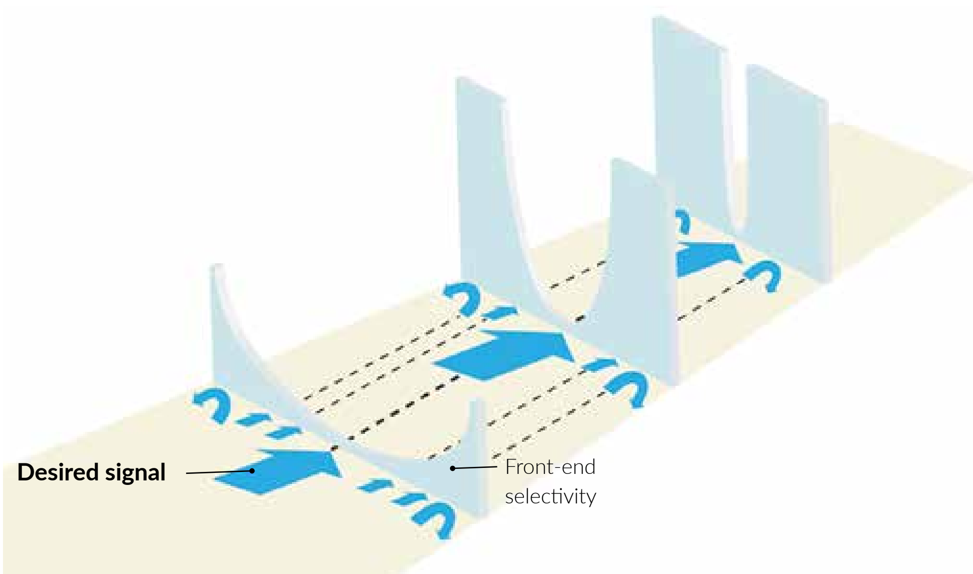


5.3: In a receiver, high-frequency signals are reduced in stages

The vulnerability is not at the end of this reducing process, but at its beginning. Remember that the initial signal was of higher frequency, and only after multiple stages of reduction was it lowered to the point where the receiver could use it. The receiver's earlier, broader stages cannot completely reject errant signals, even those several MHz away from the receiver's operating frequency.

For optimum performance, critical voltage and current levels exist at certain points throughout the front-end stages of a receiver. If these levels change significantly, the performance of the receiver suffers. This happens when a nearby transmitter's off-frequency signal enters the front-end stage.

Such signals can be several MHz away from a receiving frequency, and radiate from sources several thousand feet away, and still cause significant interference (figure 5.4).



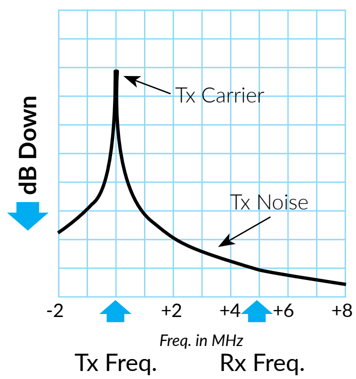
5.4: Unwanted frequencies (shown here as reflected arrows) can alter critical receiver voltage and current levels

Transmitter noise
Interference experienced by a receiver as a result of transmission power "leaking" into other nearby frequencies.

The second challenge: transmitter noise

Transmitter noise is interference caused by carrier signals just outside of a transmitter's assigned frequency. In an ideal world, a transmitter would channel 100 percent of its signal power into the narrow band of frequencies assigned to its transmission channel. In the real world, however, this level of precision is simply not possible, and the result is called transmitter broadband noise radiation, or more commonly, transmitter noise. While the vast majority of transmission power remains within the assigned channel, there remains a small fraction that "leaks" into channels above and below the intended carrier frequency.

Modern transmitters are equipped with filter circuits that eliminate a large portion of these errant signals, but even with these measures in place, enough transmitter noise escapes to degrade the performance of a receiver. As the chart below illustrates, this interference effect is most pronounced at frequencies closest to the transmitter's carrier frequency (figure 5.5), but can also impact receivers operating several MHz away.



5.5: Transmitter interference is most pronounced near the assigned frequency (shown here as Tx frequency, located at zero on horizontal axis)

We hear transmitter noise in a receiver as "on-channel" noise interference. Because it falls within the receiver's operating frequency, it competes with the desired signal and cannot be filtered out.

To illustrate this kind of interference, imagine having a conversation with someone in a crowded room. If everyone else is talking, you'll notice how hard it is to understand the other person, even if the overall noise level in the room is relatively low. That's because other voices, like unwanted transmitter noise, are similar to the voice you're trying to hear.

This is a key distinction between transmitter noise and receiver desensitization, which you'll recall comes from signals far from the operating frequency of the receiver. Consider again the illustration of having a conversation. Receiver desensitization is more like loud, disruptive sounds coming from a construction site next door. The interference is not similar to the voice you're trying to hear, but it still distracts you from the other person's voice.

How isolation helps duplex communications overcome both challenges

In duplex RF systems, transmitting and receiving frequencies are close to each other. In addition, the antennas will also be physically close, or even share a single antenna. Now that we understand the source and nature of the two interfering elements—receiver desensitization and transmitter noise—how can we overcome these interfering influences and assure reliable operation of our paired transmitters and receivers?

The answer, as you may have guessed, is proper isolation.

Earlier in this chapter, we explored how a duplex RF system required isolation between transmitter and receiver using the example of a call on a mobile device. But when applying that theory to practical application, adding isolation to the system requires some planning and a bit of math. Remember that we have not one but two sources of interference to overcome—receiver desensitization and transmitter noise—and each requires its own solution.

It boils down to two simple questions:

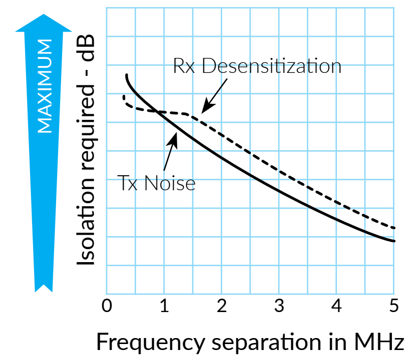
1. How much isolation is required **to prevent receiver desensitization** from the transmitter's carrier, and;
2. How much isolation is required **to reduce transmitter noise** to a lower, even negligible level?

While these are simple questions, each one has many more questions built into it, such as, but not limited to:

- How close together are the transmitter and receiver frequencies?
- What frequency band are we using?
- What is the transmitter's power output?
- What are the unique product specifications for the particular transmitter and receiver we're using?

While each application will have very different answers for these and other considerations, you can usually find the answers in the equipment manufacturer's data. For the purposes of this discussion, we'll focus instead on the broader use of isolation in duplex systems.

Determining the amount of required isolation is a matter of examining both sources of interference and identifying the optimal isolation level. As shown below (figure 5.6), we see the effect of frequency on both interfering influences, receiver desensitization (dotted line) and transmitter noise (solid line).



5.6: The effect of frequency separation on receiver desensitization and transmitter noise

In short, the closer the frequencies are to one another, the greater the need for isolation. For instance, the chart shows that reducing the frequency separation from 5 MHz to 1 MHz requires double the isolation to assure that the receiver will not be sensitized and that transmitter noise will be reduced to negligible levels.

Horizontal separation
The practice of placing a transmitter's antenna a certain distance from the same device's receiving antenna to achieve the necessary isolation.

Achieving sufficient isolation

Once we have determined the requisite amount of isolation by answering our specification questions and applying what we learned from figure 5.6, we can implement the correct degree of isolation by one of two methods:

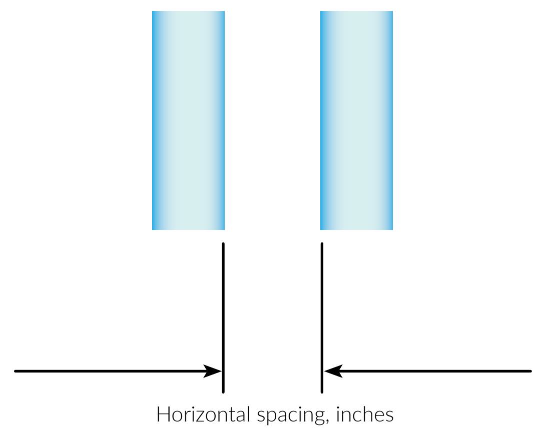
1. Use two antennas, physically separated by a given distance, or;
2. Use the appropriate duplexer with a single-antenna system.

Let's examine the first option of two physically separated antennas. Within this option, there are two ways of achieving the desired result: horizontal and vertical separation.

Method 1: Two antennas—horizontal separation

If you've ever driven cross-country with the car radio on and heard a favorite song fade to static in mid-chorus, you've experienced an effect called propagation loss. Propagation loss describes the way an RF signal loses intensity and weakens (or attenuates) as it travels across distance. This effect means that placing the two antennas apart—creating *horizontal separation*—yields a certain amount of isolation, simply by virtue of signal attenuation in the space between them (figure 5.7).

With enough distance, we can achieve virtually perfect isolation and total protection from both receiver desensitization and transmitter noise. However, even the most isolated RF system is vulnerable to interference from outside sources located nearby.



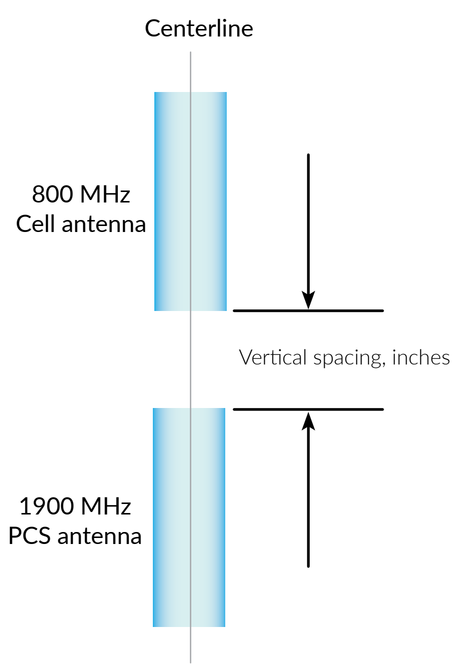
5.7: Horizontal antenna spacing and isolation

Method 1 alternative: Two antennas—vertical separation

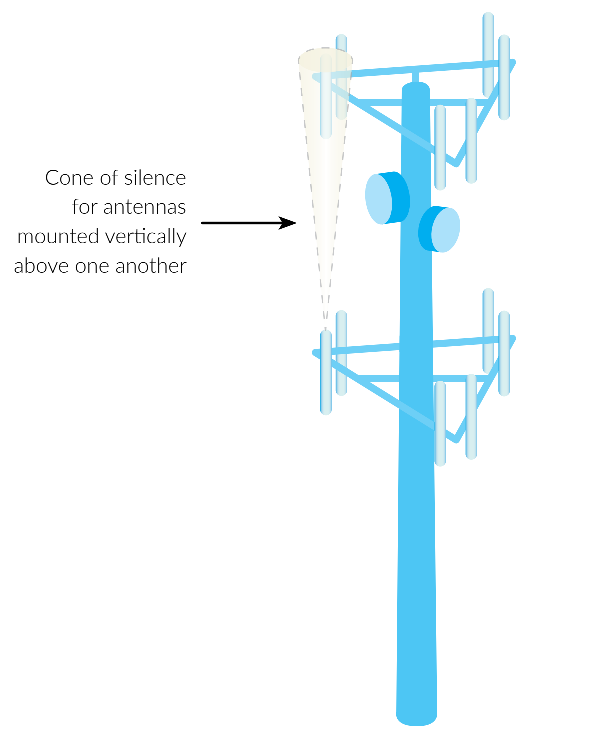
Alternately, one may achieve the same isolating effect by separating the transmitter and receiver vertically, a practice called *vertical separation*. In real-world applications, this option is more convenient and efficient as it allows both transmitter and receiver to be mounted on a single tower, one above the other, separated by the requisite distance to achieve sufficient isolation.

A secondary benefit of vertical separation is that this arrangement takes advantage of what is known as the "cone of silence" that exists between vertically stacked antennas (figures 5.8A and 5.8B).

The cone of silence is a dead zone (technically known as a null or lack of gain) that extends above and below communications antennas, allowing each to operate in the other's shadow, so to speak.



5.8A: Vertical antenna separation and isolation

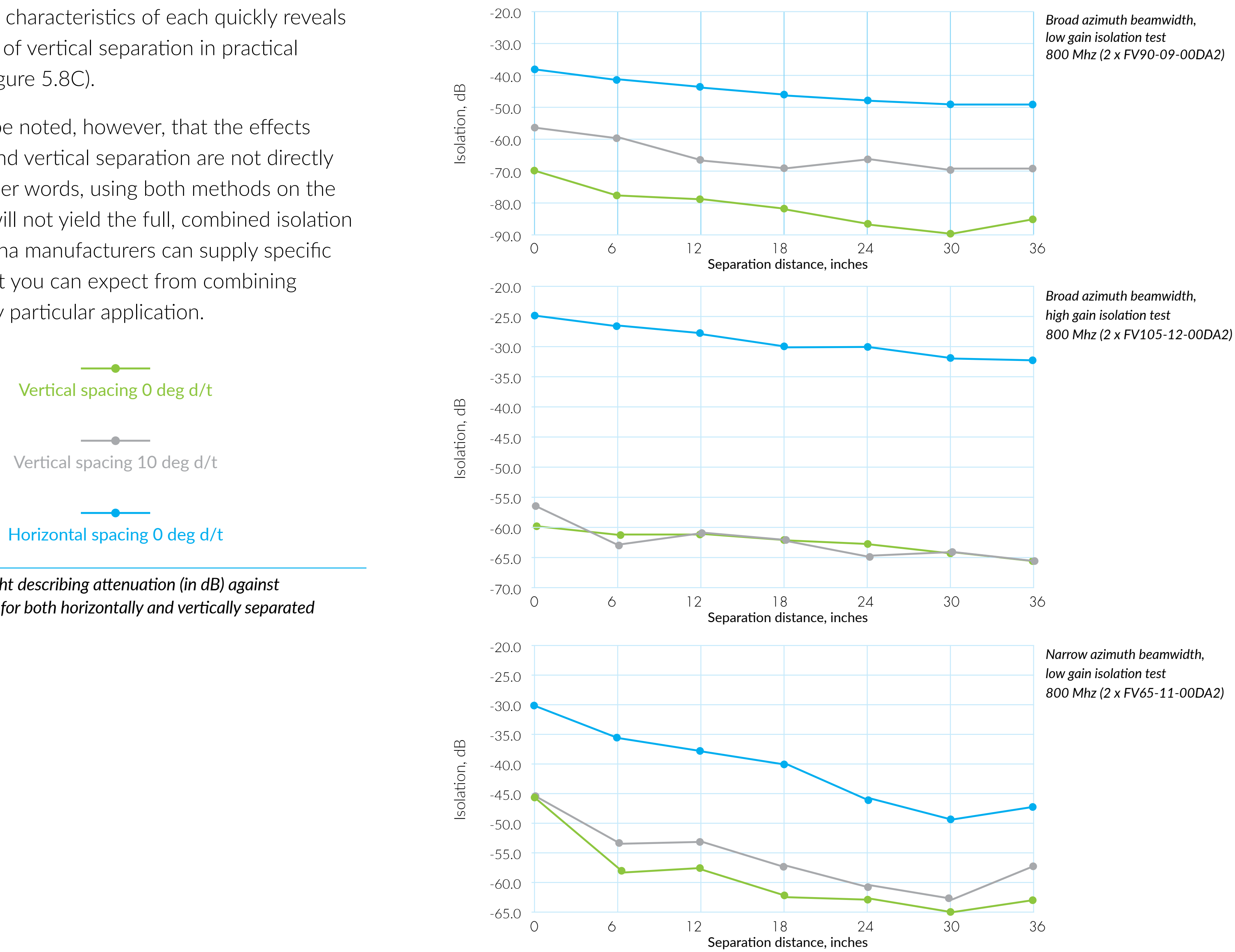


5.8B: The "cone of silence" isolates antennas directly above and below each other

Vertical separation
The practice of placing a transmitter and receiver in separate locations on a single antenna, allowing the height difference to achieve the necessary isolation.

Comparing the characteristics of each quickly reveals the superiority of vertical separation in practical applications (figure 5.8C).

It should also be noted, however, that the effects of horizontal and vertical separation are not directly additive. In other words, using both methods on the same system will not yield the full, combined isolation of each. Antenna manufacturers can supply specific figures on what you can expect from combining methods in any particular application.



5.8C: Graphs at right describing attenuation (in dB) against separation (in feet) for both horizontally and vertically separated antenna pairs

Method 2: One antenna with a duplexer

The other method of achieving the required isolation between transmitter and receiver is the use of a duplexer in a single-antenna system. A duplexer replaces one of the two antennas and two lengths of coaxial cable by allowing both transmitter and receiver to operate at the same time, on the same antenna (figure 5.9).

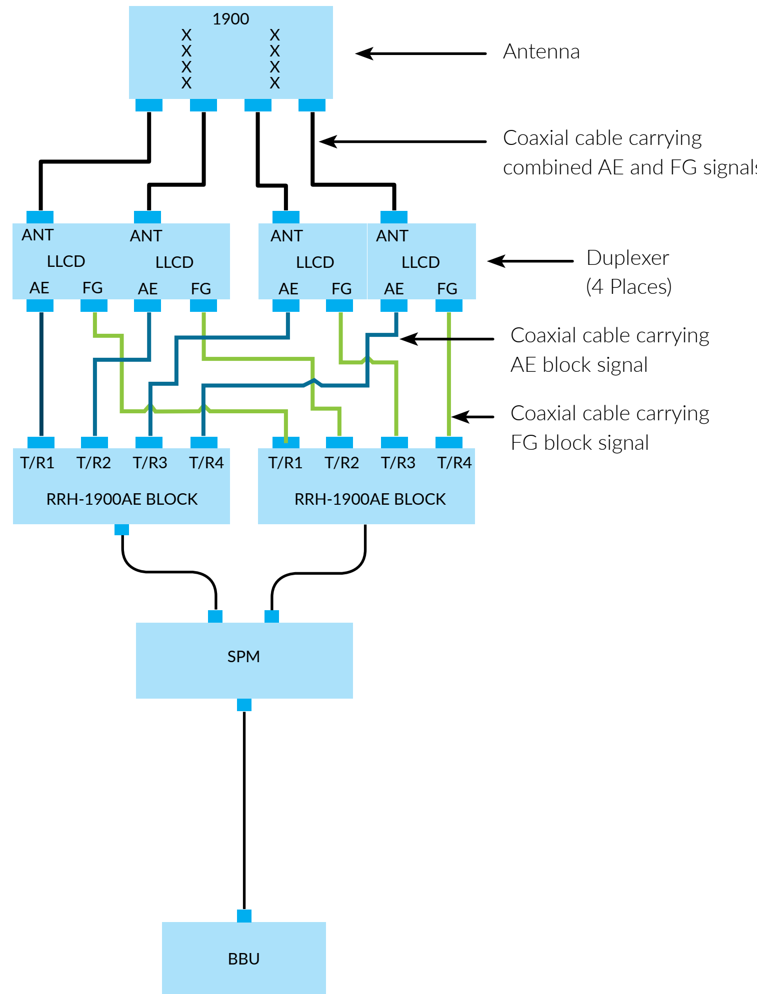
The cost benefits from this option can be significant, as a duplexer cuts the needed infrastructure in half. But the cost benefits are secondary to the other advantages, including:

Isolation. A duplexer reliably isolates transmitter and receiver, regardless of external circumstances or terrain.

Antenna pattern. Without a duplexer, two separated antennas are required. Whether arranged in a horizontally or vertically separated configuration, they cannot occupy the same space. This separation means that the coverage area of either the transmitter or receiver may be larger or smaller than the other, a variable that a duplexer eliminates.

Tower space. Leasing tower space is expensive and space on the tower is at a premium. By building or leasing only one tower instead of two, operators can realize lower total cost of ownership.

These are all good reasons to opt for a single antenna with a duplexer, but, as with every advantage in engineering, there are drawbacks as well. We'll explore these considerations a bit further on, but, for now, let's examine how a duplexer actually works and how to choose the right one for a particular application.



5.9: A typical cell site duplexer configuration

Considerations in choosing a duplexer

There are two distinct families of duplexers used in two-way RF communications: the bandpass duplexer and the band-reject duplexer. To choose the right option, it's important to consider the requirements of the system and what the correct duplexer must do. For the best results, a duplexer must:

1. Be designed to operate in the system's frequency band
2. Be able to handle the transmitter's power output
3. Operate at or below the system's frequency separation
4. Create minimal power loss to transmit and receive signals
5. Provide at least a minimum level of transmitter noise rejection
6. Deliver sufficient isolation to prevent receiver desensitization

These last two factors relate specifically to isolation and prevention of interference. In both cases, protection must meet a minimum threshold, but there is no hard upper limit, and no harm in exceeding specified isolation levels.

Losses through the duplexer

As a matter of course, the signal strength of both the transmitter and the receiver are reduced slightly in the process of passing through the duplexer. These losses are called *insertion loss: transmitter to antenna* and *insertion loss: receiver to antenna*. Like losses caused by other forms of attenuation, these duplexer losses are measured in dB and tend to increase as frequency separation between transmitter and receiver decreases (figure 5.10).

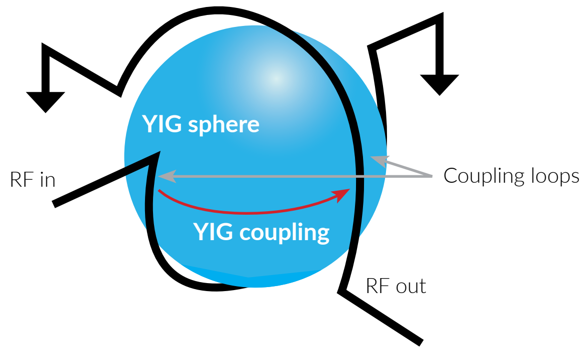
Insertion loss: transmitter to antenna	
Insertion loss	Reduced power (watts)
0.5 dB	11%
1.0 dB	20%
2.0 dB	37%

Insertion loss: receiver to antenna	
Insertion Loss	Reduced strength (microvolts)
0.5 dB	5%
1.0 dB	11%
2.0 dB	20%

5.10: Equivalent signal power loss at discrete duplexer insertion loss levels

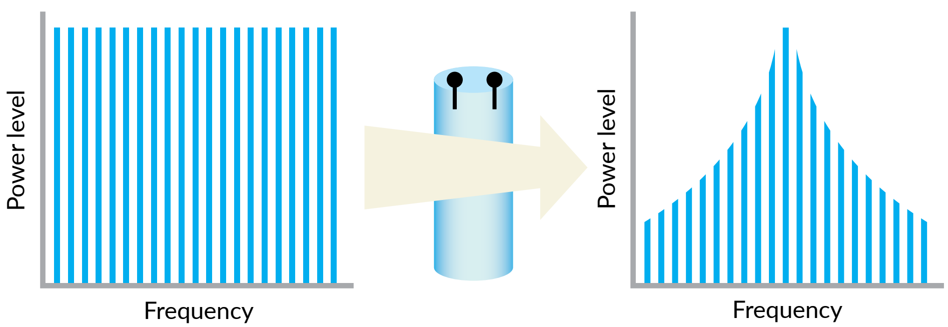
The bandpass cavity

The distinguishing feature of the bandpass duplexer's design is the *bandpass cavity*. The bandpass cavity works as a filter of RF frequencies, allowing a narrow band of desired frequencies to reach the receiver and attenuating frequencies outside this band. Energy is fed into the cavity by means of a coupling loop. This energizes the resonant circuit formed by the inner and outer conductors. A second loop couples energy from the resonant circuit to the output (figure 5.11). The loops determine the selectivity of the bandpass cavity.



5.11: The operation of a coupling loop

The narrow band of desired frequencies that pass through the cavity experience only slight loss and are all within a few thousand cycles of the cavity's *resonant frequency*. The effect of multiple frequencies, transmitted at equal power, on a bandpass cavity is illustrated below (figure 5.12).



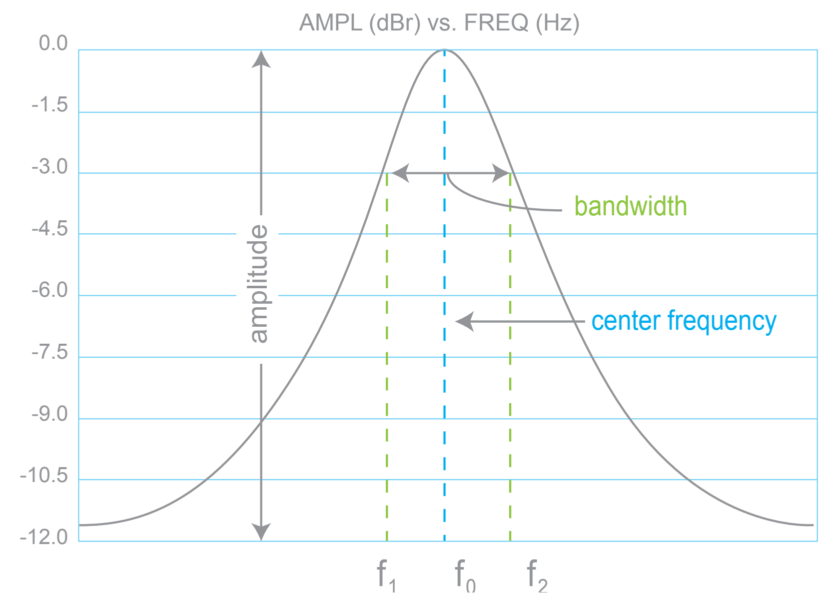
5.12: Attenuation of undesired frequencies passing through a bandpass duplexer

Bandpass cavity
A "frequency filter" that limits the channels that pass through the filter to a select set of frequencies. Other frequencies are prevented from passing. Most devices have multi-stage bandpass cavities that filter out different frequencies at each stage.

Resonant frequency
The natural tendency of a system to oscillate with larger amplitude at particular frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations.

The selectivity of a bandpass cavity is usually illustrated in a frequency response curve. This curve describes the degree of attenuation provided by the cavity at discrete frequencies above and below the cavity's resonant frequency. The curve also shows the insertion loss to the desired signal at the cavity's resonant frequency (figure 5.13).

In cases where a single bandpass cavity cannot provide enough rejection to undesired frequencies, the addition of more cavities in sequence can further refine selectivity. While this results in additional insertion loss, selectivity can be increased substantially.



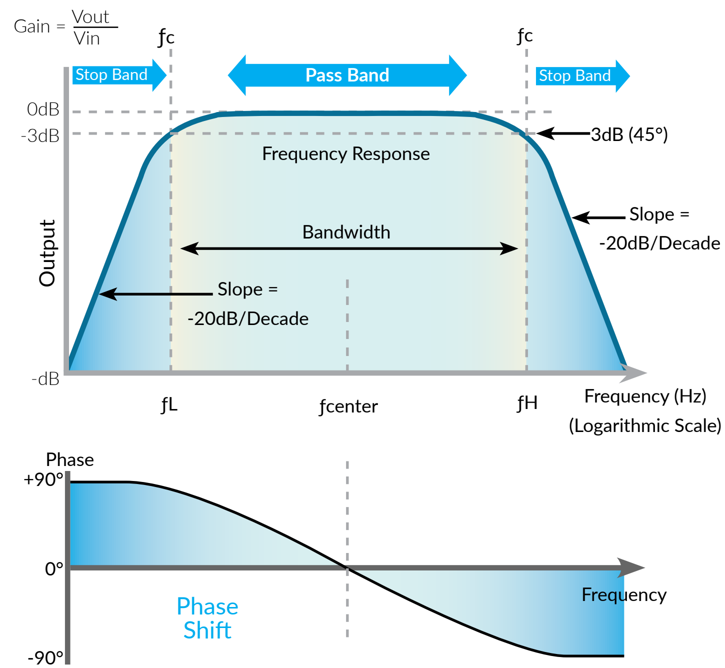
5.13: The effect of bandpass filter on multiple frequencies

The bandpass duplexer

It is the combination of two or more of these bandpass cavities—interconnected in a duplex configuration—that makes a *bandpass duplexer* work. One or more of the cavities are placed in the transmitter part of the duplexer, tuned to allow only the narrow band of transmitting frequencies to pass freely. Similarly, those cavities in the receiving part of the duplexer are tuned to the narrow band of receiving frequencies (figure 5.14).

The transmitter's output signal is filtered through the transmitter bandpass cavities of the duplexer on its way to the antenna, with the desired frequencies experiencing very little loss. At the same time, undesired frequencies are attenuated significantly, reducing the transmitter noise that could otherwise interfere with the signal.

As an added bonus, this reduced transmitter noise not only improves the signal to our own receivers, but those operating on different frequencies as well. By limiting errant frequencies, we reduce the likelihood of receiver desensitization for other users on entirely different channels.



5.14: The effect of bandpass filter on multiple frequencies

Similarly, the bandpass cavities on the receiver part of the duplexer (again, usually two or more cavities in a duplex configuration) are resonant to receive only assigned frequencies. As with the transmitter's bandpass cavities, there is a modest loss of power in the process of receiving, but unwanted frequencies are attenuated to negligible levels.

The net effect is that off-frequency signals are virtually invisible to the receiver, protecting it from desensitization—not only from its own corresponding transmitter, but from others operating on completely different frequencies.

Bandpass duplexer
A duplexer that uses multiple bandpass cavities to separate transmitter and receiver signals, allowing for simultaneous two-way communications.

Isolating the best solution

Modern two-way communications networks must contend with the interfering effects of both receiver desensitization and transmitter noise. While a two-antenna solution is one way to address these factors, most practical applications must contend with space, cost and antenna availability limits. In most cases, a bandpass duplexer provides the requisite isolation between transmitter and receiver, even when operating on the same antenna.

With the isolating properties afforded by a bandpass duplexer, both transmitter and receiver can operate efficiently while reducing transmitter noise and receiver desensitization. The result is a compact, efficient and reliable communications network that easily accommodates two-way communication of voice and data.

Behind every simple call or text on millions of mobile devices at any given moment is a world of complex science and technology at work—and now you have a better understanding of the important role that transmission and receiving isolation systems play in RF communications.

Chapter 5 summary

Duplex RF communications:

- Allow simultaneous two-way signal traffic
- Inherently vulnerable to interference and require isolation to work efficiently

Sources of interference:

- Receiver desensitization
- Transmitter noise

Isolation:

- Techniques that prevent both kinds of interference
- Measured in dB; the higher the dB loss, or attenuation, the clearer the signal

Antenna solutions:

- Polarization separation
- Horizontal separation
- Vertical separation
- Addition of duplexer

Duplexer choices:

- Bandpass duplexer
- Band-reject duplexer

Chapter 6

The many ways to connect:

RF transmission lines

Look around your home and office and you'll see wires, cords and cables everywhere. In your office, network cables connect your computer to the outside world. In your living room, coaxial cables bring in premium programming and high-definition video cables feed it to your flat-screen TV. In any room of the house, you may have a reliable land-line telephone that can reach out to virtually any person on the planet, all through a slender phone line of twisted copper.

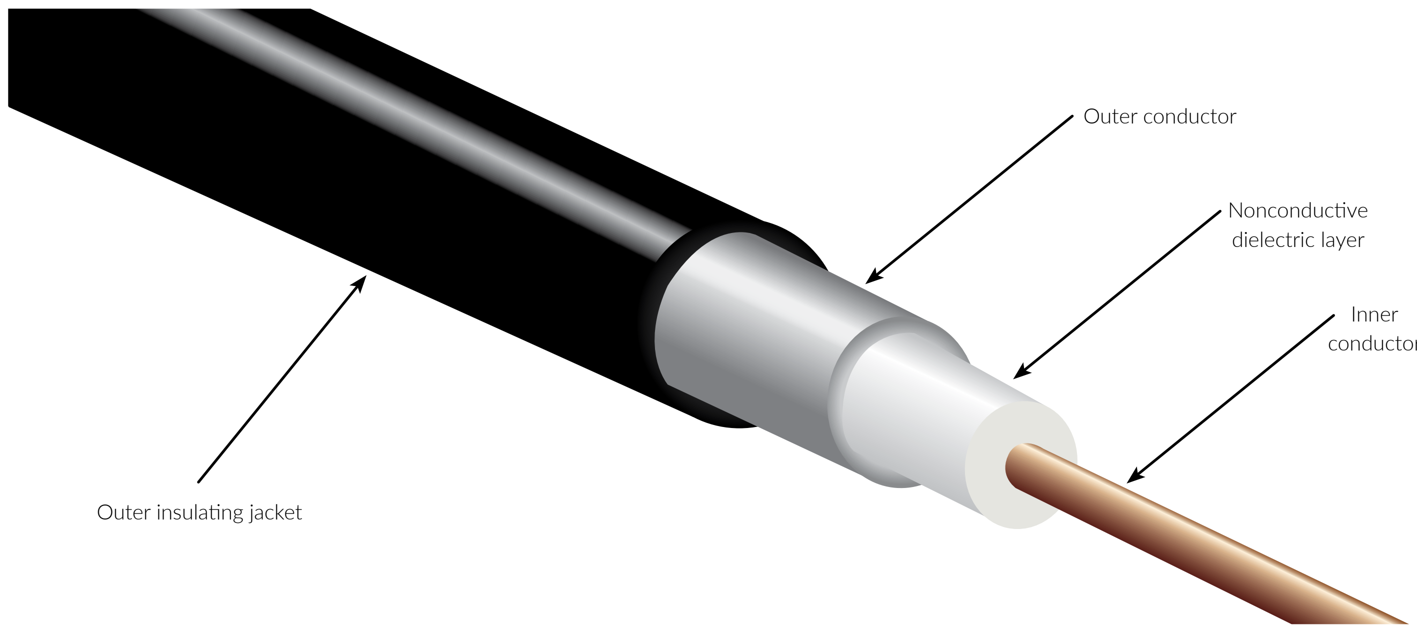
Indoors and out, these connections manage the flow of information that drives our daily lives. **CommScope** is dedicated to the continuous improvement of cable technologies that have an impact on every life, every day.

Different cables are made for an amazing variety of uses, but they all have one thing in common: *they transmit power and patterns from a transmitting source to a receiving destination.* In RF applications, these cables are the hard links that connect antennas to base stations. They are collectively known as transmission lines.

Transmission line
In RF applications, the physical medium that conducts RF power from one point to another, usually between a base station and an antenna.

Long ago, *transmission lines* were primarily used for the movement of electrical energy. Multi-conductor transmission lines could efficiently connect a power source, like a generator or battery, to a device that would consume that energy. This kind of configuration is common even today. You create a small-scale version of it every time you use an extension cord to connect an outlet to an appliance.

As telephone technology emerged, the limitations of this technique soon became apparent. When passing multiple circuits along a single transmission line, the signals proved highly vulnerable to external interference. To address this problem, Bell Telephone Laboratories developed a new type of cable in the 1930s. It was a shielded cable consisting of an inner wire surrounded by non-conductive material called a dielectric. This nonconductive material was then surrounded by an outer, sleeve-shaped conductor, and the whole assembly was finally encased in an insulating cover. If this design sounds familiar, it's because you've seen it before. This was the first coaxial cable, essentially the same design used today for data transmission (figure 6.1).



6.1: The basic construction of a coaxial cable

In RF applications, *coaxial cable* is used as a transmission line for radio frequencies that only penetrate the outer layer of a solid conductor, a transfer known as the "skin effect." The benefit of this arrangement is that it allows the outer surface of the outer conductor to be grounded.

Signals pass along a coaxial cable by riding the outer surface of the interior conductor and the inner surface of the outer conductor with a nonconductive dielectric layer between them. As a result, the only escape points for the energy carried on the line are at either end—exactly where they're needed for clear transmission.

Coaxial cable types

Modern coaxial cables used in RF transmission can be grouped into three main categories: solid dielectric, air dielectric and foam dielectric. The construction of each category makes each of them suited to particular uses.

Advantages:	Disadvantages:
Flexible Easy to install Inexpensive No pressurization required	High signal loss Prone to deterioration RF signal leakage through outer conductor
Low signal loss High power and frequency capacity Long operational life	High initial costs Pressurization logistics Vulnerability to moisture
Reduced power loss No pressurization required Moderately priced Long operational life Enhanced crush resistance	Slightly more loss than air dielectric More expensive than solid dielectric

Solid dielectric cables employ a flexible inner conductor (stranded or woven, as opposed to a solid wire), covered by solid extruded polyethylene insulation. The outer conductor is braided, and multiple layers can be stacked with shielding foil between them. The outer insulation is a polyethylene jacket.

Air dielectric cables are similar to the solid variety except that they employ open space as the inner nonconductive layer. This cavity is supported with small insulating spacers that maintain the open channel and are pressurized to keep out moisture.

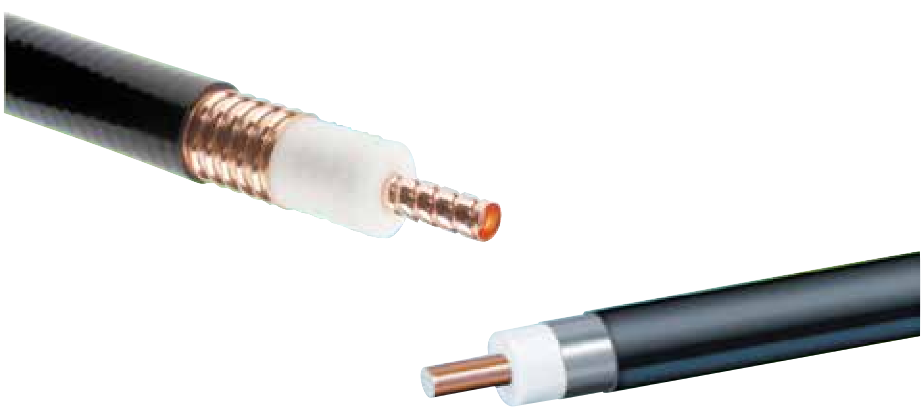
Foam dielectric cables employ a solid, as opposed to stranded, copper wire core. The outer conductor is generally smooth aluminum, corrugated aluminum or corrugated copper. The inner nonconductive layer is made of polymer foam, which combines several key advantages from both solid and air dielectric cable varieties. Its power loss and cost characteristics lay between the two other options, but foam also offers practical advantages that make it the preferred choice in many modern two-way RF applications.

Coaxial cable
A transmission line built to prevent interference while carrying multiple signals. It consists of an inner core conductor and an outer sleeve conductor, separated by a nonconductive dielectric layer.

The mechanical elements of coaxial cable

Several material choices are available for both the conductive and nonconductive elements of coaxial cable. The specific needs of a particular use determine which combination is most efficient and affordable. Below, you can see two examples of the many varieties available (figure 6.2). Note how they feature different conductive components, but both have the same solid dielectric insulator and outer jacket.

Signal energy is carried along the inner and outer conductor. You will notice that, in both cases, the surface area of the outer conductor is much greater than that of the inner conductor. Therefore, the conductive properties of the inner conductor must be as efficient as possible. That's why highly conductive copper is almost universally preferred.



6.2: Corrugated copper (left) and smooth-wall aluminum (right) coaxial cables

Braided copper is the most commonly used outer conductor on solid dielectric cables. Copper is again chosen for its exceptional conductivity, and it is used in a braided form to improve its flexibility. Solid copper or aluminum material, either corrugated or smooth-walled, is most often used for foam or air dielectric cables. The choice between aluminum and copper often comes down to cost. While aluminum is less expensive than copper, it also has lower conductivity.

In RF transmission lines, the preferred dielectric material is polyethylene due to its low loss characteristics and long life span. This material can be used in either solid or foam dielectric constructions, or as the spacers in an air dielectric design. For high-power applications, Teflon is substituted for its high melting temperature due to the higher operational temperatures. Teflon is more expensive, so there are various other materials with costs and temperature resistances between those of polyethylene and Teflon.

Electrical properties of coaxial cable

Signal loss, or *attenuation*, is a significant consideration in the design of a cable. The loss occurs in three ways:

1. **Conductor loss** is direct function of the conductive properties of the cable's materials.
2. **RF leakage** is a measure of the effectiveness of a cable's shielding.
3. **Insulation** loss is a fixed degree of attenuation inherent in the material of the cable's dielectric layer.

Attenuation is measured in decibels; in the specific case of transmission lines, attenuation is expressed in either decibels per 100 feet of cable length or decibels per 100 meters of cable length.

How well these losses are managed depends on such factors as the size and length of the cable, the conductivity of the materials used in the cable, the frequencies traveling along the cable and the effectiveness of its shielding. There are general physical rules governing how these factors impact attenuation, such as:

Cable size. As a rule, a cable's conductor loss will decrease as its size increases. This is due to a larger cable's broader cross-section and its corresponding increase in conductive area.

Cable design. Solid outer conductors allow less RF leakage than braided ones, though at the expense of flexibility.

Dielectric material choice. By choosing any particular dielectric material, you can anticipate a predictable level of insulation loss. As explained earlier, air dielectric offers the lowest insulation loss, while solid dielectric comes with the highest loss.

Assigned frequency. All three types of attenuation directly increase as a function of the frequency of the cable's signal. The higher the frequency and the shorter the wavelength, the greater the loss in any given cable.

This complex balancing act of performance, ease-of-handling and cost means no single transmission line design is ideal for all, or even most, circumstances. Each design is an exercise in compromise between these factors.

Attenuation
Measured in decibels (dB), this is the loss of power experienced by an RF signal as it moves from one point to another. Transmission line attenuation is expressed in either decibels per 100 feet (dB/100 feet) of cable length, or decibels per 100 meters (dB/100m) of cable length.

Ohm
The unit of electrical resistance. In terms of RF transmission lines, ohms refer to the inherent, or characteristic, loss over a length of cable.

Characteristic impedance

Characteristic impedance, commonly called cable impedance, is a measurement of the electrical resistance of an RF transmission line as measured in *ohms*. The figure is derived by a complex formula involving the ratio between the cable's two conductors. As a general rule the industry standard impedance for RF cable is usually 50 ohms (though some applications require 75 ohms).

This expected degree of impedance can be affected by imperfections or damage in the cable itself. A deep dent in the outer wall of a coaxial cable can cause its impedance to vary from its standard level. This disruption is called a discontinuity, or a change in the distance between the inner and outer conductors, as you might see from a squashed cable. The signal refelects within the cable, creating the same loss of performance as a mismatch between cable and antenna (chapter 3).

This is one reason that a cable's flexibility and crush resistance are such crucial factors. Damage during installation is a frequent source of discontinuity and can be expensive and time-consuming to remedy.

Velocity of propagation

Simply stated, the velocity of propagation within a coaxial cable is the speed at which a signal can travel along that cable. Velocity is governed by the amount and type of dielectric used, and is expressed as a percentage of the speed of light. It can range from 67 percent for solid dielectric cables up to 92 percent for air dielectric cables. However, since the speed of light is more than 670 million miles per hour, velocity is rarely a concern in itself, though there are exceptions. For example, velocity becomes significant in cases where phasing is required (chapter 3).

Power handling capability

The amount of power that a particular transmission line can handle is dictated by two measurements of temperature: the ambient temperature (the temperature of the air surrounding the cable) and the temperature of the cable itself under ordinary operation.

As we've seen, power loss is inherent in any cable design, and is dependent upon the kind of dielectric used in the line. This lost RF power translates to heat, so the greater the attenuation within a cable, the more heat it will generate from that lost energy. Likewise, the greater the frequency passing along any given cable, the more heat it will generate as a function of loss.

Heat resistance is a critical factor in cable design. For instance, foam dielectrics begin to soften near 180 degrees Fahrenheit, so an engineer choosing the right transmission line will need to be certain that the combined internal and ambient temperatures won't exceed 180 degrees. If the cable exceeds its limit, the softened dielectric will allow the inner conductor to shift, creating a discontinuity. If it should contact the outer conductor, the result would be a shorted cable. To help engineers make the right choice and prevent such failures, cable manufacturers like **CommScope** rate each type of cable for certain power levels at certain ambient temperatures.

RF leakage

As its name suggests, RF leakage is a function of the physical ways an RF signal can "leak" out of a transmission line. In the case of a cable with a braided outer conductor, there are countless tiny openings in the cable. As with a leaky garden hose, the more power or pressure you apply, the more significantly those leaks affect performance.

In addition to attenuation, RF leakage causes another challenge when several high-power braided coaxial cables are arrayed in close proximity to one another. The leakage can cause interference between the cables at their endpoints, such as when they connect to antennas, multi-couplers, duplexers and so forth. Faulty connections can make this problem worse.

As with power handling, RF leakage is included in a cable's specifications to help engineers choose the best option for any particular configuration, especially in circumstances where many cables terminate close together.

Environmental factors
The climate and setting of a cable installation dictates what kind of cable should be used. Considerations include:
- Sunlight UV exposure
- Humidity and moisture
- Temperature extremes

Cable life expectancy

The expected useful life span of a coaxial transmission line depends largely upon *environmental factors*. Since engineers have little control over these factors, they must compensate by choosing the right design with the right materials to assure the longest possible life span.

The composition of the cable's outer jacket is one of the more obvious considerations. Most flexible and semi-flexible coaxial line jackets use polyethylene, polypropylene, or polyvinyl chloride (PVC). All three options are vulnerable to long-term sun exposure, so manufacturers incorporate carbon black into the resin to improve the jacket's resistance to aging under ultraviolet light, which can extend their operational lives up to 20 years of service. This improvement is why so much coaxial cable you see in household use is black.

Moisture and humidity are important factors as well. While water can infiltrate through tiny nicks, cuts or age cracks in the cable, the single most common form of moisture infiltration is through improperly sealed connectors on the ends of the cable. Even humid air present inside the connector can condense as temperatures fall, resulting in liquid water that wicks deeper into the cable along the outer conductor's braid. This can potentially corrupt the entire cable and short the inner and outer conductors, particularly in the connectors themselves. The result is increased signal reflections within the cable and degraded passive modulation performance.

Connectors

As the number of modern RF applications has grown, the technology used to connect a cable to its terminus has evolved. The simple designs created in the 1940s for military uses have diversified and improved into a variety of types such as these (figures 6.3 through 6.8).

UHF connectors are the oldest and most popular type still in use for two-way communications. They are rugged, reliable and easy to install, which is why they are the preferred choice for applications with frequencies up to 300 MHz.

BNC connectors are small, quick-disconnect versions with a bayonet-style locking coupling. These are often used on narrow cables connecting equipment.

TNC connectors are similar to BNC connectors, but include threaded connections that keep them secure in environments where vibration is a concern.

Type-N connectors are an industry favorite for RF communications with frequencies above 300 MHz, where UHF connectors are not suitable. Type-N connectors may be rated to perform at 10 GHz or even higher.

EIA flanges are used primarily on pressurized air dielectric cables operating above 450 MHz. These connectors offer the standard 50 ohms of impedance and typically offer higher voltage characteristics than Type-N connectors.

DIN (Deutsche Industrie Normenausschuss) connectors are available in several sizes and have come to dominate the RF communication industry as a whole. They have a larger cross-section than Type-N connectors, and better withstand the rigors of field installation.

For exceptionally congested installations with multiple service carriers operating in the 700, 800, 900 and 1900 MHz bands, silver-plated Type-N or DIN connectors are required.

6.3: DIN coax connector

6.4: BNC coax connector

6.5: TNC coax connector

6.6: Type N connector

6.7: EIA flange coax connector

6.8: UHF coax connector

Voltage standing wave ratio (VSWR)
A key measurement of cable performance and signal quality. It quantifies the amount of signal reflected backward along a cable to its source. Theoretically, perfect operation yields a VSWR value of 1.0, or "unity," meaning zero reflections.

Installation step 1: cable choice

As discussed above, choosing an appropriate cable depends on knowing:

- Which frequencies it will carry
- How much loss is tolerable
- Where it will be installed
- What kind of budget limits exist

In most cases, there will be more than one acceptable cable solution for any one of these four criteria, but the key is to get the greatest possible benefit against all four. For instance, if we look at cost as the primary driver, we see that smaller-diameter cables cost less to purchase and install, but will need more upkeep and eventual replacement. We may also consider a less expensive option with a higher rate of loss, intending to compensate for that loss through greater RF power generation on one end of the cable or increased antenna gain on the other.

Installation step 2: field testing

Once you have selected and installed the cable that best performs to your application's priorities, the process of fine-tuning that performance can begin. There are three tests you would likely perform: inner and outer conductor continuity, shorts between conductors, and a *voltage standing wave ratio (VSWR)* test.

The first two tests are simple and direct measurements of impedance in the cable, performed with an ohmmeter. Any physical disruption of the cable's integrity would be revealed in a non-standard level of impedance, and you could begin inspecting the cable for the source of the problem.

The third option, the VSWR test, is an indirect but ultimately more revealing measurement of overall line performance. Basically, the VSWR test measures the amount of signal reflection taking place within the cable. Measuring both forward and reflected power with a wattmeter, you can compare the values against the cable manufacturer's conversion chart for that particular type of cable. If everything is functioning correctly, the observed amount of reflected energy should fall within expected limits. Poorly made connections or connections with mismatched impedance will quickly become obvious. This process is explained in more detail early in chapter three.

Installation step 3: troubleshooting

Reduced RF communication performance can be rooted in any number of problems, occurring in any component in the system. When the antenna and transmitter have been ruled out as potential trouble spots, it's time to examine the transmission lines because a lot of things can go wrong with cables.

Here are just a few things that can cause system performance to drop suddenly:

Weather. A good place to start is to visit the site itself and speak to those familiar with recent weather trends. A bad storm, lightning, hail or high winds can damage cables and loosen connectors.

Local phenomena. In addition to weather, other local events can impact performance. Explosions from nearby mining operations, small earthquakes, even a stray bullet from a hunter's gun have been identified as culprits.

Water infiltration. As discussed earlier, water is perhaps a cable's greatest enemy. Checking connectors for signs of moisture, double-checking their seals, and examining the cable itself for any new damage will help confirm or rule out water as a cause.

In any event, once the damage has been identified, that section of cable cannot be taped or otherwise repaired. It must be replaced. Long-term system performance degradation can be just as serious, and is often caused by cable aging. While metal-sheath cables are almost impervious to aging when properly installed, inferior cables can age and crack with extended exposure to the sun's UV rays and extreme temperatures.

Localizing the problem

If your VSWR measurements reveal a high level of reflection—say, 20 percent above the level indicated by the manufacturer's table—then, most likely, your cable is experiencing an open, a short or a partial short somewhere along its length or in a connector. To confirm this, you could perform the following tests:

1. Open the top of the cable and short the inner and outer conductors (the cable ground should be removed for this). Measure impedance between the conductors with an ohmmeter. An intact cable will show low impedance between the two, while high impedance will reveal damage to the outer conductor. This kind of damage is hard to locate. If economically feasible, replacement may be the best option.

2. Remove the short between the conductors and test impedance again. In this instance, an intact cable will show high impedance, while low impedance may indicate damage to the inner conductor that creates a short somewhere within the cable. The damage required to cause this kind of fault often leaves more obvious traces on the outer jacket and is easier to identify.

3. Examine the connectors themselves. Type-N connectors are particularly vulnerable to misalignment and pin breakage, which can result in a short. Also, as the primary source for any potential water infiltration, it's a good idea to examine any type of connector for signs of moisture. For best results, check connectors during cool weather or at night, where any trapped vapor will have condensed into more visible droplets.

4. Practice good preventative maintenance. Proper installations reduce the need for ongoing maintenance, but vigilance is always to your benefit. Any time an installation is realigned or painted, it's smart to inspect the cables and connectors. Identifying small problems before they become big problems can save a great deal of time and money and minimize lost performance.

In summary, a solid understanding of the construction of cables helps you understand their best applications, where they may be vulnerable, and where to look when a fault is suspected.

Transmission lines connect the world

While so much of modern RF communication is comprised of radio energy radiated through the air, the critical links on either end depend on the right kind of transmission line cable and the right connectors between base station and antenna.

As a physical link, these cables must be able to flex where they're needed, withstand the punishing elements, and faithfully carry the frequencies that eventually reach you as your internet connection, land-line call, or mobile phone call virtually anywhere in the world.

You live among small-scale examples of the same technology at home. From the USB cord on your computer mouse to the century-old design of your telephone's wall cord, each cable is designed to carry specific frequencies over specific lengths, each one for a unique purpose. As a leading provider of coaxial and other transmission line products for networks all over the world, **CommScope** is at the forefront of the race to develop innovative solutions that will address the future of technology tomorrow.

Chapter 6 summary

RF transmission lines:

- The bridge between base station and antenna
- Adapted from designs once used to carry simple electricity

Coaxial cable:

- Characterized by insulated inner and outer conductors
- Solid dielectric
- Air dielectric
- Foam dielectric

Mechanics and materials:

- Copper used for inner conductor
- Copper or aluminum used for outer conductor
- Polyethylene used for dielectric insulation
- Various connectors for different applications

Design considerations:

- Cable impedance
- Velocity of propagation
- Power-handling capability
- Heat and frequency limits

Measuring performance:

- Conductor loss
- RF leakage
- Insulation loss
- VSWR testing and fault detection

Chapter 7

Making every connection count:
Passive intermodulation (PIM) fundamentals

It's a fact of life for electronic devices: when something isn't working correctly, we check the connections. From the most complex cellular transmission system to the simplest toaster, junctions between cables and components are the most likely place for problems to occur.

But beyond the obvious culprits like poor connections, water infiltration or mechanical issues, a communications system's connections can also play host to other problems. One example is *passive intermodulation (PIM)*, an inherent product of the system's frequencies and their associated harmonics. PIM can create undesirable sideband frequencies that interfere with the system's assigned frequencies. It takes a knowledgeable partner like **CommScope** to choose the right components and assist in the design and installation of a communications system.

Passive intermodulation (PIM)
A potential side effect of having more than one high-powered signal operating on a passive device such as a cable or antenna. PIM occurs at non-linear points in a system such as junctions, connections or interfaces between dissimilar metal conductors, creating interfering frequencies that can decrease efficiency. The higher the signal amplitude, or power, the greater the effect.

Intermodulation explained

The growing demand for wireless services has increased the complexity of system design and the resources to support that demand. As a result, there are more RF components, configurations and spectrums utilized in the RF path. Included in these additional components are passive devices that can contribute to PIM. With a good understanding of these PIM contributors, we can proactively address PIM and its impact on the system noise floor.

Because PIM will act as a component of the overall noise floor, we will first discuss the components of system noise and how noise impacts network performance. The system uplink noise floor is dynamic and affected by PIM and other factors. It is also driven by the number of active users. For every new user added to the site, additional noise is added to the network, causing a "noise rise". As new users raise the noise floor, each user must deliver a higher power transmit signal to overcome the increased noise. This means the user must be closer to the receiving cell tower. Consequently, the cell coverage area is reduced.

There is a theoretical limit to "noise rise" and a consequent corresponding limit to the number of users that can be added. This theoretical maximum number of users is referred to as the "pole capacity" of the network.

Uplink pole capacity is proportional to the system signal-to-interference/noise ratio (SIR) and several other variables and, for WCDMA networks, can be estimated using the following widely accepted formula:

Np = (W / R)/((1+ f) * AF * 10^(EbNo/10))

where

Np	= Pole capacity
W	= Spreading bandwidth
R	= Users' radio bit-rate
f	= Ratio of other-cell interference to in-cell interference
AF	= Activity factor
Eb/No	= Ratio of energy per information bit to power spectral density of noise + interference

Notes:

1) Basically, Eb/No represents the amount of gain that must be provided above noise and interference for acceptable system performance

2) Eb/No can be expressed as Eb/No = Processing Gain + SIR, where SIR is the Signal-to-Interference/Noise ratio

3) For 3G voice at a CS12.2K data rate, the Eb/No requirement is typically 5 dB

An example pole capacity calculation estimating the uplink capacity for a WCDMA cell site is shown as follows:

Np	= Pole capacity
W	= 3.84 Mhz (value for 3G UMTS)
R	= 12,200 bits/second (value for CS12.2K for 3G UMTS voice)
f	= 65% (typical network value)
AF	= 50% (typical network value)
Eb/No	= 5 dB (typical value for 3G UMTS)
Np	= (3840000 Mhz / 12200 bit/s) / ((1+0.65) * 0.50 * 10^(5 / 10))
Np	= 20.6 users maximum

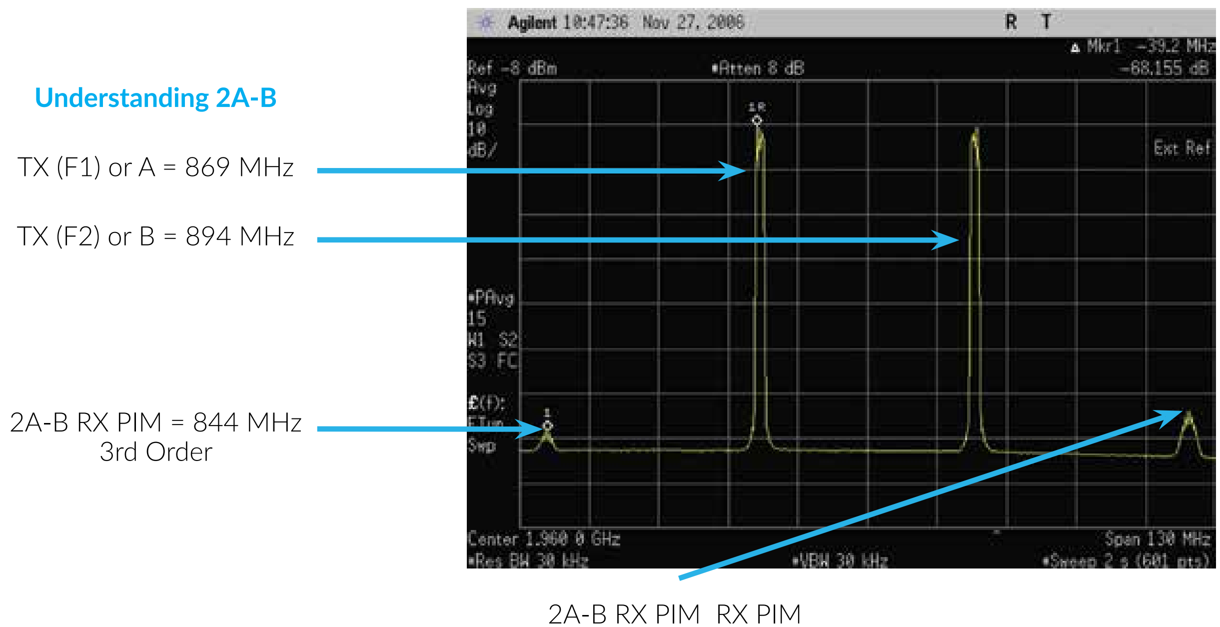
We can see from the above pole capacity equations that increases in the system noise floor can degrade system performance, increase system power consumption and reduce cell coverage area. Because PIM, when not mitigated, can be a significant contributor to noise, it is clear now the serious impact it can have on wireless network performance.

Now that we have developed an understanding of the system level impact of PIM, we will describe specifically how PIM is generated and how it can be mitigated.

Generally speaking, intermodulation is the result of two or more frequencies (often, a duplexed system's receiving and transmitting frequencies) interacting with one another according to certain mathematical relationships related to their specific frequencies. The effect creates errant signals that contribute to noise and interfere with the system's operation.

Passive intermodulation is a particular kind of intermodulation that takes place in the passive parts of a system—such as cables and antennas—often at connections that create nonlinearity in the system.

As the complexity of communications systems has increased, so has the potential for PIM, making it a top priority for service providers to manage its effects. In a cellular base station, for example, a transmitting frequency can create PIM interference in its own receiving frequency, or vice versa. Where PIM occurs depends on the separation of the two main frequencies, as shown in the chart below (figure 7.1).



7.1: Calculating where PIM will occur, based on two example frequencies, A and B; in this example, PIM occurs at 2A-B (a common 3rd order product) and again at 2B-A

Calculating potential PIM

In this example, transmission frequency A (869 MHz) and transmission frequency B (894 MHz) create potential PIM problems at 2A-B (844 MHz) and at 2B-A (919 MHz). This means we must expect troublesome interference if our reception frequencies include 844 MHz or 919 Mhz.

Nonlinearity

A location within an electrical circuit where voltage does not remain consistently proportional to power. This effect is caused by imperfect connections between components and cables.

Managing PIM

Since we don't always have the freedom to select frequencies that avoid PIM issues, we need to look at other methods of reducing its influence in our communications system. Reducing PIM levels starts with reducing nonlinearity in the circuit.

Nonlinearity in a passive RF circuit typically results from current rectification at the conductor joints and mechanical junctions. Resolving nonlinearity generally means improving connections throughout the RF path of the system. This means addressing problems such as:

- Improper connector attachment
- Poorly torqued connections with incorrect contact pressure
- Contamination or corrosion of conducting surfaces
- Inadequate plating on rust-prone ferromagnetic components
- Poor connections due to cold solder joints

The most common and visible contributors to high PIM levels in the system are associated with the mechanical and physical integrity of the connections in the RF path. Therefore, those who deal directly with the RF components in the field, such as installers, service technicians and test engineers are integral in the battle against PIM. They will require training in proper field installation, proper use of PIM test equipment and a fundamental understanding of PIM.

In order to manage PIM, we also need to understand the environment in which we are performing the PIM testing. For a manufacturer, it is now common for PIM to be tested in a controlled RF environment such as an anechoic chamber. This is done to ensure the device under test has an isolated and "quiet" RF environment to confirm the PIM performance as it relates to the published manufacturer specification.

Field testing presents an entirely different set of challenges if PIM performance testing is required. This is not an isolated or "quiet" RF environment. This noisy RF environment can negatively impact PIM or provide false PIM levels that are a direct result of the environment. In other words, you may obtain PIM levels in your testing that are not reflective of the actual device under test, but rather the RF environment in which it is tested. Shown on the next page are some examples of base station antenna testing where the environment impacted the PIM measured in the field.

Although conditions such as external RF signals or the test environment may not be controlled, the selected components, installation practices and testing are within our control. Education and awareness are the first steps in managing the difficulties associated with field PIM testing.

System PIM calculators

Reducing PIM in the RF path is important and challenging. CommScope provides several PIM system calculators to support your RF path analysis.

Download the latest tools below.

PIM and VSWR System Calculator (Global)

Learn more

Band and Block Second and Third Order PIM Calculator (North America)

Learn more

Band and Block Second and Third Order PIM Calculator (EMEA)

Learn more

Clear sky
-123 dBm (-145 dBc)

Towards forklift
-84 dBm (-127 dBc)

Person nearby with phone, keys, adapters, and badge
-94 dBm (-137 dBc)

Near shelter
-102 dBm (-145 dBc)

Pointed at fence
-102 dBm (-145 dBc)

Near cabinet and test equipment
-96 dBm (-139 dBc)

7.2: PIM measurements—field observations

- *On-site antenna measurements with iQA200 portable PIM*
- *Clear sky RF field-of-view required to avoid any secondary PIM sources which could cause false PIM failure*

Researching, testing and installing

The severity of PIM is directly related to signal amplitude, or power. That's why PIM performance of different RF components specify power levels along with their other properties. Typically, this figure is calculated by applying two signals of close frequencies at 20 watts (+43 dBm), the industry standard for PIM testing. This standard helps assure that comparisons between different products yield meaningful answers.

Understanding the PIM properties of components like cables, connectors, combiners, filters, tower-mounted amplifiers and antennas allows you to design a system with minimal exposure to potential PIM issues. It's a meticulous process, but it's essential to preventing potentially crippling PIM problems later on:

- Choose a knowledgeable provider that has demonstrated experience in the PIM specification of their products—one who can help you make the right component choices. **CommScope** makes this expertise freely available to our customers.
- Test your component performance against PIM specifications to assure trouble-free operation later on.
- Use trained installers certified in preparation and installation techniques. Since they will be managing connections, and connections are the source of PIM, their skill is your best guarantee against problems.

By following these recommendations, you can count on an RF system that will operate efficiently, virtually free of troublesome PIM effects.

PIM: best addressed at the planning stage

In engineering, connections are perennial trouble spots. Each connection, junction and interface is an opportunity for something to go wrong, including passive intermodulation (PIM).

The only way to design the system to mitigate PIM is to study and test the PIM specifications of the components comprising that system, which is why partnership with **CommScope** is so vital. We provide the experience and insight to spot potential trouble early in the process. Visit the PIM-dedicated portal of our website, to learn how we can assist you with awareness, prevention, identification, resolution and support.

Chapter 7 summary

Passive intermodulation (PIM):

- Caused by interactions between multiple frequencies and their harmonics
- Can cause transmission or receiver frequencies to interfere with each other
- Occurs as a byproduct of nonlinearity in a circuit, such as at a connection
- A critical consideration in the selection of components and installation of those components in an RF system

The infrastructure behind the connection:

Microwave backhaul

Imagine two kids, each standing in their own backyards, talking to each other on soup cans connected by a string. This is the simplest of connections, nothing more than two users on a direct, point-to-point, dedicated line. This same simplicity applies if we replace the cans with walkie-talkies—the communications system is still reliant on just two points of contact.

Once the system becomes more complex, like modern distributed communications networks with millions of users, these simple connections are no longer practical or possible. A centralized processing point is needed to route many conversations simultaneously just to make the correct phone ring when you dial its number.

This centralized processing is called *backhaul* and it's the infrastructure behind the connection where you'll find many **CommScope** solutions.

Backhaul
The process of connecting two ends of a transmission through a central routing point.

To imagine backhaul in action, consider the classic image of an early 20th-century telephone operator, manually connecting calls at a switchboard. As more and more people call at the same time, the task soon grows very complex—eventually, too complex for humans to perform.

Today's modern cell phone networks require much more complex connectivity—collectively called backhaul—than even the fastest human operator could provide. The process of routing network traffic for a cell phone call requires many steps to complete, and looks something like this:

1. Mary makes a call to John on her cell phone from her office
2. Mary's outbound call is picked up by the nearest cell tower
3. The tower routes Mary's call to the area's regional network
4. The regional network sends Mary's call to the national network
5. The national network routes Mary's call to Bill's regional network
6. The regional network broadcasts Mary's call from the nearest cell tower
7. Bill's cell phone rings, he answers and the call connects

Backhaul is the process of routing Mary's cell call—and all network traffic—up to, then down from the core processing backbone between the cell tower nearest to Mary and the one nearest to Bill. While backhaul can be achieved over a number of different materials, such as twisted-pair copper cable, fiber optics or coaxial cable, microwave backhaul offers a time- and cost-efficient backhaul link, ideally suited to cell phone networks that move calls and data across the country and across the world millions of times every day.

Microwaves and the electromagnetic spectrum

The electromagnetic spectrum includes an incredible variety of radiation types, all expressed in Hertz (Hz), a measurement of a particular radiation's frequency. Most frequencies used in electronics are expressed in thousands of Hertz, or kilohertz (KHz); millions of Hertz, or megahertz (MHz); billions of Hertz, gigahertz (GHz) or even trillions of Hertz, terahertz (THz). Some of the more familiar types are listed below (table 8.1).

Frequency	Wavelength	Application
50–60Hz	6000–5000km	AC electricity transmission
3–30kHz	100–10km	Sub-marine communication
30–300kHz	10–1km	Long-wave radio broadcast
180–1600kHz	1.7km–188m	AM radio broadcast
1.8–30MHz	167–10m	Shortwave radio
88–108MHz	3.4–2.7m	FM broadcast
300–3000MHz	1–0.1m	UHF point-to-point
700–2700MHz	0.43–0.11m	Mobile base station
0.3–300GHz	1–0.001m	Microwave/Millimeter Backhaul
352, 230, 193THz	1550, 1300, 850nm	Fiber-optic links
420–750THz	714–400nm	Visible light

8.1: Applications associated with different radiation wavelengths within the electromagnetic spectrum

Microwave backhaul frequencies

The International Telecommunications Union (ITU) regulates the microwave spectrum available for backhaul applications. Each band is best suited to particular situations of topography, climate, bandwidth requirements and cost, determined in large part by their typical hop lengths, or the distance each band can travel in open air between points (table 8.2).

You may notice that the table includes several "unlicensed" frequency bands. While most microwave frequencies are regulated to prevent interference during hops, unlicensed frequencies are unregulated, requiring cooperation between operators to prevent interference.

The highest bands, 60 GHz and 80 GHz, possess unique propagation characteristics, as shown in their very small maximum hop length. They serve a special purpose which we will discuss later in this chapter.

Frequency band	Frequencies (GHz)	Typical maximum hop length (km)	Typical minimum hop length (km)
0.9 (unlicensed)	0.902–0.928	100	–
2.4 (unlicensed)	2.4–2.5	100	–
4	3.6–4.2	70	24
5	4.4–5.0	60	16
5 (unlicensed)	5.3, 5.4 & 5.8	50	–
L6	5.925–6.425	50	16
U6	6.425–7.125	50	16
L7	7.1–7.75	50	10
U8	7.75–8.5	50	10
10	10–10.7	20	10
11	10.7–11.7	20	10
13	12.7–13.25	20	6
15	14.4–15.35	20	6
18	17.7–19.7	20	2
23	21.2–23.6	20	2
26	24.25–26.5	20	2
28	27.5–29.5	15	2
32	31.0–33.4	10	1.5
38	37.0–40.0	10	1
42	40.5–43.5	10	1
60 (unlicensed)	57.0–66.0	1	–
80	71–76/81–86/92–95	5	–

8.2: Typical hop lengths for microwave frequency bands

Duplex communications
A transmitter and receiver that work in different time slots or frequency slots on the same device.

Microwave advantages

The microwave band possesses characteristics ideal for radio transmissions, including those from cell phones:

- They help directional antennas make hops from point to point in narrow beams that don't interfere with each other
- The low end of the band (below 11 GHz) propagates over long distances, ideal for long-haul connections to users in remote locations
- The higher end of the band (above 11 GHz) propagates over shorter distances, ideal for short-haul connectivity required in urban locations

In addition to their technical characteristics, microwave links also offer practical and financial advantages over cable solutions, which have made them the preferred choice for modern communications networks:

- Less expensive to establish and operate
- Faster deployment
- Greater bandwidth than twisted-pair copper, critical to high-traffic applications like modern cell phone networks
- Readily scalable to handle more traffic as required
- Very reliable to operate

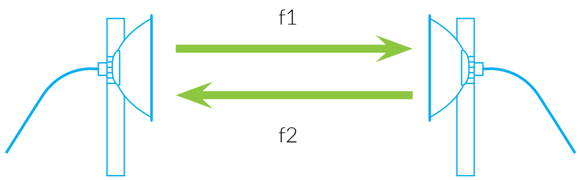
Microwave backhaul in action

Let's revisit the process of making a cell phone call. The user dials the call and the cell phone connects with the nearest cell tower, operating on the network's radio frequencies (within the 700–2700 MHz part of the spectrum). The cell tower hands off the call to a microwave transmitter (typically into one of the bands between 6–40 GHz) which directs it via a directional beam—a hop—to a collection or aggregation center which, in turn, makes the connection to the mobile network's core network. The traffic is then routed across the network to the region closest to the receiver's location, where it will be transmitted again by microwave to the nearest cell tower.

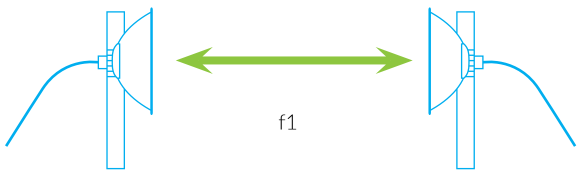
The receiving cell tower station down-converts the microwave signal back to the network's radio frequencies for its final journey to the target cell phone. The process is reversed for traffic moving in the opposite direction.

This two-way microwave backhaul generally uses a frequency-division duplex (FDD) system that allocates frequency channel pairs for simultaneous two-way, or *duplex communication* (figure 8.3).

Another way to achieve duplex communication is via a time-division duplex (TDD), which achieves the same goal by switching the required direction of transmission in a very fast, precise manner (figure 8.4). While a more efficient option, TDD requires very careful timing control and is not the preferred system for microwave use.



8.3: Frequency-division duplex (FDD) system with separate go/return frequencies



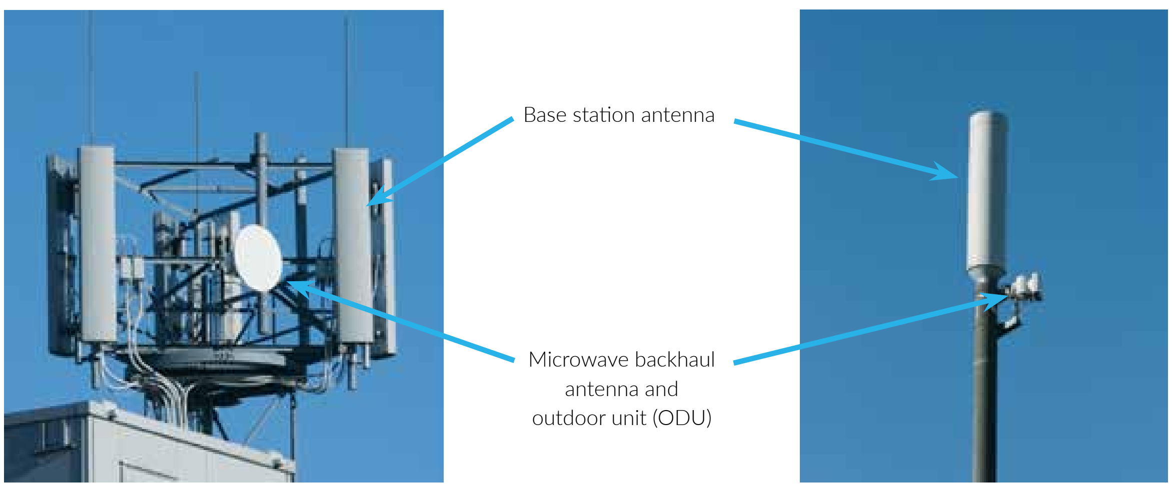
8.4: Time-division duplex (TDD) system using just one go/return frequency

Typical microwave deployments

Hop connections between microwave transmitters and receivers usually require *line-of-sight* (LOS) clearance. LOS means both ends can literally "see" one another without any obstructions in between—including the curvature of the Earth's surface. For this reason, microwave antennas are often mounted on towers or at the top of high buildings for best LOS clearance.

To maximize the value of these choice locations and to reduce the costs for leasing these locations, microwave backhaul antennas are often mounted adjacent to base station antennas, which also rely on altitude for efficient operation (figure 8.5).

Line of sight (LOS)
The unobstructed space between transmitter and receiver. Longer hops must even account for the curve of the Earth as an obstruction.



8.5: Typical microwave backhaul antenna integrated into a base station antenna location

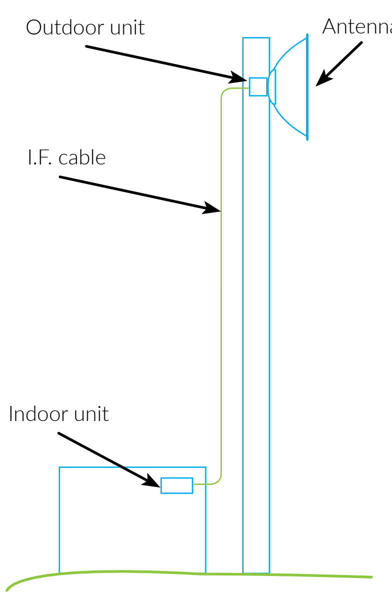
Split-mount radio system
A two-stage connection that lets microwave radios located in an indoor unit (IDU) receive and transmit through an antenna fitted with an outdoor unit (ODU).

Many short-haul installations, typically operating above 11 GHz, use a *split-mount radio system*, which divides the radio into an outdoor unit (ODU) and an indoor unit (IDU). The ODU houses the microwave circuitry, including the go/return microwave signal separating diplexer and the up/down frequency converters. It is mounted in an enclosure adjacent to the antenna, or more frequently integrated into the antenna assembly itself (figure 8.6).

The IDU contains the modulator/demodulator, more commonly known as a modem, and the control circuitry necessary for translating the cell phone traffic into a form suitable for microwave transmission.

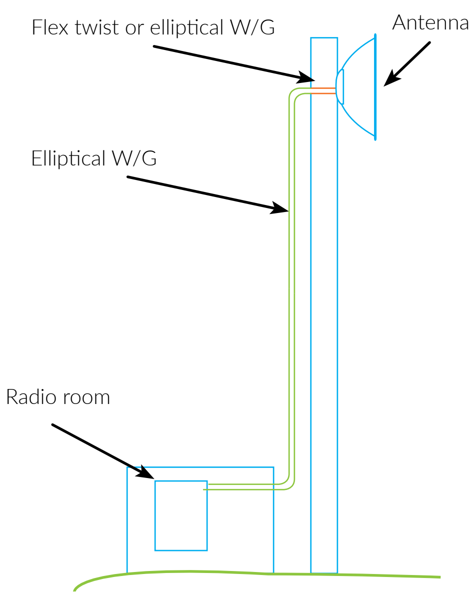
For high-density traffic and long-haul hops, multiple radios are typically housed in a remote radio room adjacent to the base of the tower. Generally, these hops use larger antennas operating at frequencies under 11 GHz (figure 8.7).

Connections between the antenna and the radios are made by coaxial cable, elliptical waveguide or circular waveguide transmission lines, depending on the frequencies involved (figure 8.8). Chapter 6 provides detailed information on transmission lines.



8.6: Typical split-mount microwave radio system showing IDU and ODU

8.7: A typical lower frequency aggregation point

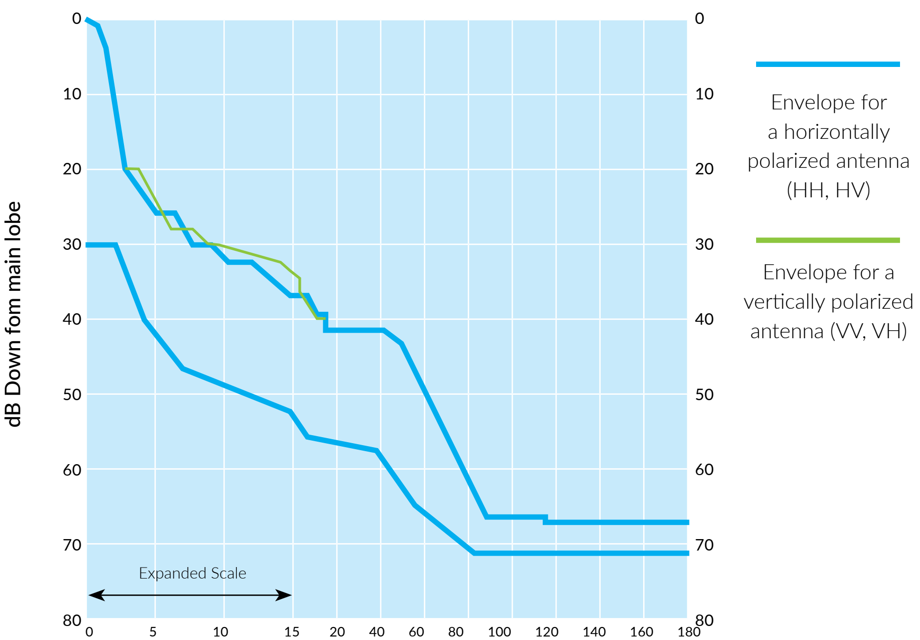


8.8: Connections between remote microwave radios and a microwave antenna

Planning a microwave link

When considering a new microwave backhaul path, it is important to consider potential interference issues during the design process. The planned link must not interfere with adjacent links or other operators in the area. To prevent conflicts and other problems, you must consider:

- Frequency coordination with other links in the vicinity
- Radio and radiation characteristics of the antenna
- Transmission power levels



8.9: A typical radiation pattern envelope (RPE) document

To avoid these issues, industry standard software tools such as iQ-link®XG from **CommScope** can smooth the planning process and assist in regional overview. Antenna manufacturers offer assistance as well, providing planners with the radiation pattern envelope (RPE). An RPE document includes a performance summary and the key specifications related to antenna gain, beam width, cross-polar performance and radiation patterns (figure 8.9).

The chart describes the directional properties of the antenna by mapping it directionality (in dB) against its azimuth angle. As this chart shows, the envelope has a main beam area at zero degrees, corresponding to the electrical axis of the antenna. This is the line-of-sight direction, where the directionality is at its maximum.

Away from the main beam, the directionality quickly decreases. This corresponds to a drop-off in antenna sensitivity, whereby signals transmitted or received away from the on-axis direction reduce rapidly. The link planner uses this information to determine how much of their new proposed link signal will deviate from the intended direction and assess whether this is likely to present problems (e.g., interference, threshold degradation, etc.

Because of their importance in the planning process, RPE documents are strictly regulated. In Europe, the European Telecommunications Standards Institute (ETSI) publishes several classes of envelope standards that all antennas must satisfy. A Class 2 antenna may be permissible in locations where interference is not an issue, but cannot be used where a Class 3 antenna's stricter standards are required. The importance of using Compliant Class 3 or better specification antennas is discussed in further detail in a later section.

Most regions across the globe have adopted ETSI standards with the notable exceptions of Canada, Australia and the United States, which have their own regulatory envelope minimum standards.

Signal polarization
The orientation of a signal's electric field relative to the ground. It may be horizontal or vertical.

Protecting microwave systems from the elements

Like every stage in the chain of communication, backhaul must be reliable and available at all times. Downtime means lost revenues, irritated customers and expensive repairs. In practical terms, downtime is measured as a percentage, or in minutes per year (table 8.10). A detailed explanation of reliability predictions and measurement can be found in chapter 10.

Downtime, minutes per year	Availability
525.6	99.9000%
52.56	99.9900%
26.28	99.9950%
5.256	99.9990%

8.10: Downtime in minutes per year and corresponding availability percentages

This growing need for reliable communications within realistic budget constraints is partly what drives demand for microwave backhaul. However, due to its open exposure to the elements, certain reliability-limiting factors are unavoidable:

- Precipitation and moisture
- High winds
- Temperature variances
- Lightning strikes
- Atmospheric refraction

Fortunately, each challenge to reliability has an available mitigating measure.

Rain and snow

As mentioned earlier, lower-frequency microwave bands propagate very well across long distances, allowing hops of 50 km or more. In fact, the most significant limiting factor is not distance itself, but atmospheric conditions. Rain falling through the signal path reduces signal strength, an attenuating phenomenon known as "fade."

In frequencies above 11 GHz, rain-induced attenuation becomes more pronounced, reducing hop distances accordingly. Rain, and to a lesser extent, snow, can scatter signals in these frequencies. The impact depends on the rate of precipitation, the frequency involved and the signal polarization (the orientation of the signal wave, which may be horizontal or vertical).

Horizontal signals are more adversely affected by rainfall due to the shape of raindrops as they fall, so vertical polarization is the preferred choice for any link-planning.

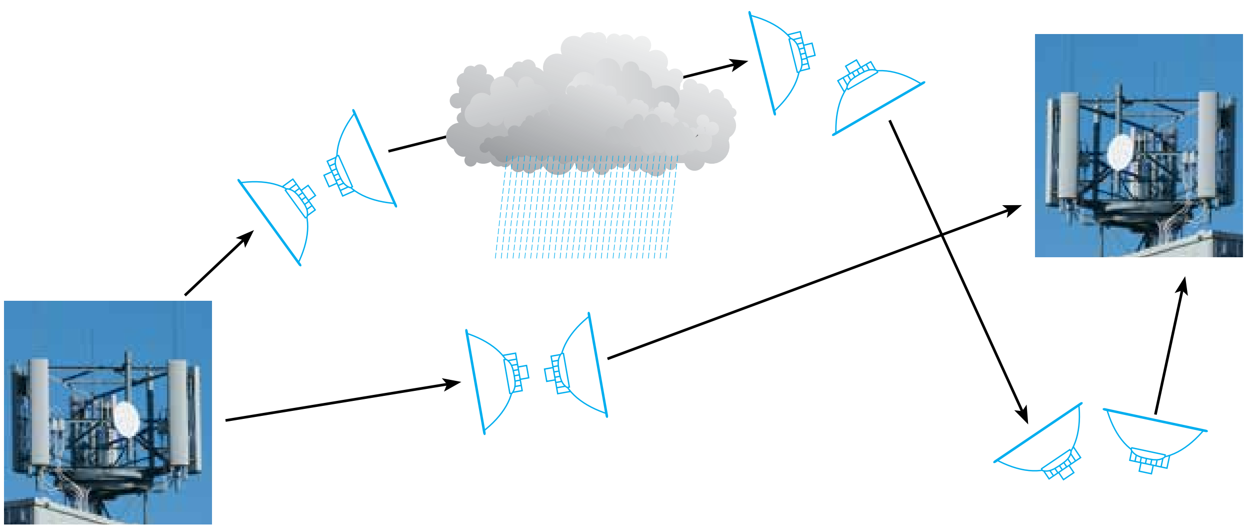
Fortunately, it is possible to mitigate these effects based on the calculations of rain outage models, building a safety margin into the transmission's power levels to compensate for expected loss and assure a reliable hop between stations. Modern microwave radios will even adjust power on the fly when needed, using an automatic transmit power control (ATPC) system.

Precipitation also interferes with polarized transmissions through an effect called polarization rotation, which essentially turns a signal's polarity enough to interfere with other signals. To counter this effect, a cross-polar interference canceller (XPIC) samples signals in both polarities in order to produce a wave that cancels out the interfering, "rotated" part of the signal.

Adaptive modulation

Another technique gaining widespread acceptance in microwave backhaul applications is called adaptive modulation. In addition to compressing, or modulating, network traffic into smaller bandwidths at higher signal levels, adaptive modulation adjusts the amount of modulation in response to any link impediments. The result is that adaptive modulation can dynamically reduce traffic to compensate for the impaired signal level while still maintaining the link, albeit with lower capacity.

Mitigation methods can also be built into link designs themselves. In multiple-hop situations, mesh and ring topologies provide alternative signal paths that bypass problematic hops by rerouting around them. Path selection is dynamic and adapts on the fly to changing conditions (figure 8.11).



8.11: Network topology with dynamic routing paths

Automatic transmission power control (ATPC)
A system that dynamically raises transmission power to overcome the effects of interference.

Microwave antennas with specialized adaptive modulation schemes

Radome
A wind- and water-proofed fabric or plastic cover that protects an antenna from the elements.

Fog

Fog only presents a challenge to the highest microwave bands above 60 GHz. Unlike rain, snow and other precipitation, it presents no real obstacle to lower, more commonly used microwave frequencies.

Temperature

By itself, temperature has little effect on microwave signals. However, if water vapor is present in transmission lines, it can condense there and impede performance when the temperature drops. The effect is similar to the attenuation caused by rain.

The hardware effect

In addition to climate effects on transmission, weather also affects a microwave installation's physical integrity. Snow or ice accumulation on an antenna introduces critical weight considerations for the antenna's design, as well as for the components installed there.

Long-haul antennas generally employ a fabric enclosure, or *radome*, that protects sensitive components from wind or moisture infiltration. Ice shields offer additional protection from falling ice, either from the antenna itself or from positions above it (figure 8.12).

8.12: Ice accumulation on a radome-protected installation

Wind

The force of wind on an antenna structure is called wind load, and it can present a serious threat to tower-mounted equipment. Wind speeds rise with altitude, so a breeze at ground level can become a gale a few hundred feet up. This is why antennas are designed to ensure mechanical integrity under all anticipated environmental conditions, typically able to withstand 180 km/h (112 mph) winds without moving on their mounts. Above this speed, some flexibility may be permitted, with a topmost survival rating approaching 250 km/h (155 mph) wind speeds.

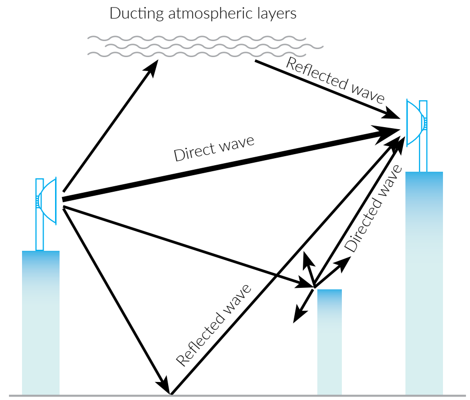
Far below these extreme limits, an antenna will flex and move slightly, even in moderate winds, within its engineering standards. While this helps maintain the integrity of the structure, it introduces an obvious challenge to LOS transmissions that depend on precise targeting between links. To ensure that this slight movement doesn't interfere with a successful hop between stations, these temporary misalignments must be factored into the antenna's power budget.

Lightning strikes

Installed in open, unobstructed locations, microwave antenna towers are natural targets for lightning strikes. If a strike passed through the antenna itself, serious damage to sensitive components would result. To avoid this danger, low-resistance earth-paths—in effect, lightning rods—are installed to direct lightning strikes away from critical components. For a full exploration of how to guard against lightning, see chapter 11.

Atmospheric effects

Atmospheric effects can disrupt reception, particularly for lower-frequency signals. Under some circumstances, a signal may essentially be received twice, first by its intended LOS connection, and then again as a slightly delayed echo of itself as a result of atmospheric refraction or ground reflection. The tiny timing difference can mean the signal arrives out of phase, in effect interfering with itself. This effect is known as multipath fading or dispersive fading, as illustrated at the right (figure 8.13).



8.13: Dispersive fading creating out-of-phase signal echoes—delayed signals bounce off the ground and vertical obstacles, and also refract in the atmosphere

8.14: A typical vertical space diversity arrangement

Option 1: space diversity

To counter the effects of dispersive fading, we can add a second, uncorrelated parallel microwave transmission path, separated vertically (figure 8.14) or horizontally.

Because the two paths don't share exactly the same space, their signals don't encounter exactly the same fading effects. The practical result is that the receiver has the option of accepting its signal from the path that happens to be less disrupted at the time.

Option 2: angle diversity

Another countermeasure is angle diversity, which requires only one antenna instead of the two. However, that antenna requires two vertically separated feed systems. While a less expensive option, angle diversity is also less effective than space diversity and is used only where a second antenna cannot be added to the installation.

Option 3: frequency diversity

Frequency diversity is another means of combating atmospheric or dispersive signal loss. A secondary, standby channel operates at a different frequency from the main channel. Since different frequencies propagate differently, two signals of different frequencies don't experience the same attenuation, doubling the chances of clear reception.

Flat fading
Total signal loss caused by atmospheric refraction. It is the result of a signal being bent completely out of its LOS connection with its receiver.

Flat fading

Flat fading is another atmospheric hazard for low-frequency signals. Unlike dispersive fading, the entire channel is attenuated because refraction has disrupted the LOS connection over the hop, so it misses the receiver entirely. A second, uncorrelated microwave path or increased power via ATPC can counter this effect.

Improving network reliability

Some of the reliability-limiting factors can be avoided by using compliant spec antennas from a reputable manufacturer. With the pressure to minimize total cost of ownership, it is tempting to purchase the lowest price antenna option, but you must also consider ongoing operations expenses in budget calculations. An inexpensive install may end up costing far more than a more expensive antenna with better characteristics for your application.

Noncompliant antennas are not simply identified by cheaper prices. They also include design problems that can spell trouble from day one (figure 8.15). Generally, they are:

- Not tested and feature non-repeatable designs
- Prone to deteriorate too quickly, resulting in RF leakage, moisture ingress and degrading metallic components
- Used with third-party add-ons for normal operation, which introduce new opportunities for corrosion, vibration and other loss of integrity.

8.15: Example of RF leakage in a noncompliant microwave antenna

The hidden costs of noncompliance

CommScope recently conducted a study to measure the cost and benefits of using lower-quality, noncompliant antennas. In this study, we examined three types in the 15, 18 and 23 GHz bands. In actual operation, the true costs began to emerge:

- **19% of the backhaul network failed** in the 15 GHz band
- **29% of the backhaul network failed** in the 18 GHz band
- **21% of the backhaul network failed** in the 23 GHz band

Obviously, these failure rates are unacceptable to most modern applications. Choosing a compliant antenna, even a more expensive one, offers benefits that can save money and hassles once the antennas are in operation, such as:

- Less potential external noise
- Less RX threshold degradation
- Longer hops
- More link availability
- More capacity
- More efficient use of the spectrum

In addition, there are other initial cost savings that aren't necessarily reflected in the antenna price itself, such as:

- Smaller antennas with lower shipping costs
- Lower landed cost
- Lower tower leasing cost

It all adds up to lower total cost of ownership, which makes good sense and means good business. There are a few common-sense steps you can take to avoid noncompliant antennas and assure your network's availability and reliability. They all start with choosing a reputable supplier.

1. Take advantage of your supplier's resources to demonstrate structural integrity under all anticipated environmental conditions.
2. Review the supplier's antenna interface design data and test range facilities for each integration type.
3. Avoid third-party add-ons that don't qualify at the integration level; the third-party supplier won't have this information, but your antenna supplier should.

This basic due diligence will pay off in reliability, speed and total cost of ownership.

Co-channel dual-polar (CCDP) operation
Using both horizontal and vertical polarity of a single frequency to double available bandwidth.

Network capacity and managing demand

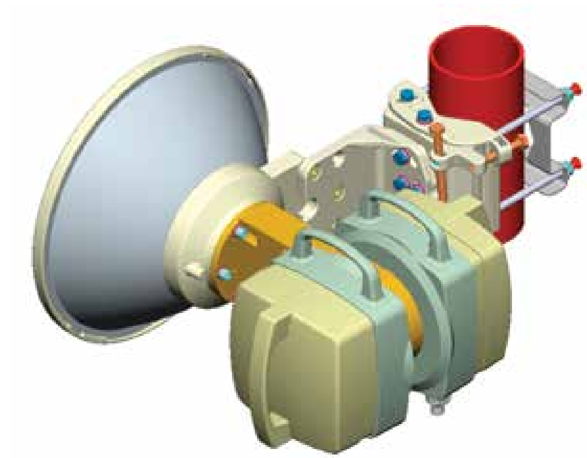
Simply put, capacity is a network's ability to handle transmission traffic. In the case of cell communications, this traffic means voice and data—often, a great deal of data. As capacity demands continue to rise with the spread of long-term evolution (LTE) and 4G mobile devices, smart planning becomes even more important to assure headroom for tomorrow's data-hungry applications.

Modulation. One way to boost capacity along a microwave link is called modulation. By employing different modulation schemes, more traffic can be squeezed into the limited bandwidth available when needed. The tradeoff is that higher modulation schemes require higher signal-to-noise performance to maintain the integrity of the data, boosting operating costs. Plus, any disruptive effects like those described above create bigger problems than they do for un-modulated traffic.

Adaptive modulation. Recently, adaptive modulation has become a universally adopted technique to help operators balance traffic and reliability needs. Adaptive modulation scales the amount of signal modulation employed as a function of the link's condition. So, if rain or other factors are present, modulation is dialed down to maintain error-free, if somewhat slower, traffic rates. When the link condition improves, modulation is automatically increased to take advantage of prevailing conditions.

Co-channel dual-polar operation. Another capacity-boosting technique leverages the polarization characteristics of microwaves themselves, which allow two streams of traffic to travel the same bandwidth at the same time—one vertically, one horizontally. This technique is called *co-channel dual-polar* (CCDP) operation.

CCDP is often used in short-haul antenna systems where an integrated dual-polarized antenna is created using an Ortho-mode transducer (OMT) to attach two ODU radios to a single antenna. This arrangement maintains a high level of isolation between the two signals for maximum clarity (figure 8.16).



8.16: An example of an integrated dual-polarized antenna

Microwave capacity

With all these capacity-boosting tools at our disposal, modern microwave backhaul data rates typically range between 32 and 155 Mbps (megabits of data per second).

However, as technology and techniques continue to improve, much higher data rates are becoming possible and economical. In the near term, 1 Gbps (gigabits of data per second) single-channel systems are coming online now.

The future of microwave backhaul

Explosive demand for mobile communications drives the need for cost-effective microwave backhaul, which, in turn drives new innovations. Old technologies are replaced by new, more efficient ways of moving data faster, more reliably and at less cost. Microwaves form the backbone of these new technologies.

For instance, legacy networks built on circuit-based transmission protocols maintain their connection regardless of how much, if any, traffic is actually being transmitted at any given time. This was once necessary to carry voice communications, but the world has moved on and this technology isn't efficient in our on-demand data world. Packet-based microwave radios encode traffic from multiple sources and routes it through IP over Ethernet, so it only utilizes bandwidth as it's needed, reducing wasted energy and capacity.

Capacity and coverage

Improved network coverage is another critical requirement for emerging mobile technologies, such as long-term evolution (LTE) and 4G mobile networks. Customer-level access is required in all regions if high-speed connectivity is to be available as a constant resource, and the ongoing rollout of base stations (known as macro-cells) offers more and more coverage to broad geographical areas.

At the same time, the capacity available from these macro-cells diminishes with distance from the base stations, requiring the addition of smaller coverage micro-cells to sustain capacity. Pico-cells represent a further layer of coverage for built-up urban areas. Both micro- and pico-cells require backhaul connectivity, and that means microwave links.

The techniques of tomorrow

There are currently a number of studies researching which type of backhaul medium will be most suitable for these new scenarios, and it seems likely that a mix of the various technologies will form the networks of tomorrow. Non-line-of-sight (NLOS) schemes using unlicensed bands offer one method of small-cell backhaul, allowing signals to turn corners and avoid obstacles in urban environments where LOS systems aren't as effective as they are in the open.

In other exciting developments, there seems to be great promise in the recently opened 60 GHz unlicensed band. At these high frequencies, the oxygen in the air itself can absorb signal power, making it suitable for short hops, often less than a single kilometer. While this may seem like a limitation rather than an advantage, an urban environment benefits from this short-hop option because they offer high data traffic rates and have such limited ability to interfere with one another from one pico- or micro-cell to another.

Lastly, the recent opening of the E-band spectrum (71-76 GHz, 81-86 GHz and 92-95 GHz) promises to open new avenues for high-capacity microwave backhaul. Operating under a light-licensing regime, very wide channel assignments (n × 250 MHz) are available to operators, making 1 Gbps data rates a real possibility without the restrictions of high-level modulation schemes.

With so many advances in recent years, and so many still to come, this is truly an exciting time in communications.

Backhaul makes modern communications possible

The ever-increasing complexity of modern communications networks demands more efficient and innovative ways of managing backhaul. In our wireless age, microwave backhaul moves the information that moves the world forward.

Though an efficient and cost-effective means of moving data through central processing, microwaves face challenges and limitations from weather, topography and interference from other nearby links. Smart planning and the right equipment can overcome these obstacles, allowing microwaves to connect us to one another wherever we may be.

As children, we first experienced the idea of backhaul as a length of string between two soup cans or the scratchy sound of a walkie-talkie. As adults, backhaul has become a key part of daily life as we depend on our cell phones, computers and other devices to connect with friends, family, colleagues and the world at large.

From strings to radio waves to microwaves, backhaul is the technology that keeps us all connected.

Chapter 8 summary

Microwave backhaul

- Communications moving through a centralized routing center
- Accomplished via links or "hops" from station to station

Microwave deployments

- Rely on line-of-sight between hop points
- Can connect multiple radios to antenna via paired ODUs

Issues affecting reliability

- Rain, snow and hail
- Wind loads
- Ice buildup on antennas
- Lightning strikes
- Dispersive fading

Avoiding external interference

- Coordinate with other links in vicinity
- Use manufacturer RPE to choose specifications

Avoiding trouble

- Choose a reputable supplier
- Look at entire cost, not just the purchase price

Maximizing capacity

- Adaptive modulation
- Co-channel dual-polar operation

Chapter 9

The energy that connects the world:

Powering wireless networks

Every year, our reliance on always-on technology grows. We expect to be able to place a call or surf the Internet with our cell phones at any time, under any circumstances. However, the electrical infrastructure that powers our networks has not kept pace with the explosive growth of cellular access—and certainly hasn't kept pace with our expectations of 24/7 availability.

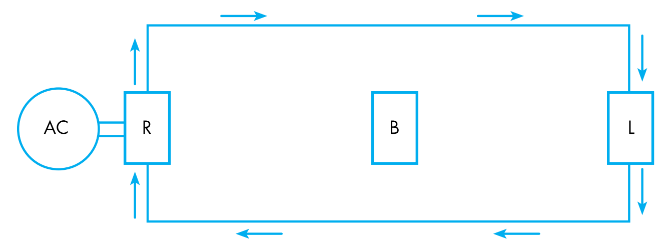
In previous chapters, we have explored some of the intricate and complex ways different components in a cellular base station come together to work efficiently and reliably. So far, the idea of powering these stations has been taken for granted. In real life, however, we don't have this luxury. Power supply connection is a very real challenge, and planning for the inevitable outages and interruptions is critical to keeping the network operating, no matter what complications may arise.

Direct current (DC)
An electrical current that runs continuously in a single direction, making it well suited for use in motors and electronic components such as semiconductors. Batteries also produce DC current.

Alternating current (AC)
An electrical current that changes polarity (direction) 50 to 60 times per second. It offers significant efficiencies when transmitted across power lines, making it the standard current for household use.

DC vs. AC power

The core technology that drives modern communications runs on *direct current (DC)* electricity. DC is different than the *alternating current (AC)* we use in our homes and offices. Since electrical power sent across transmission lines from power plants is AC, a device called a rectifier is needed to convert the AC current to DC before it can be used by the communications equipment.



9.1: Basic power system diagram—arrows indicate the DC current's direction

The rectifiers' output is connected to both the radio and its transmission equipment—the "load" for the current—as well as the backup battery equipment (figure 9.1).

Why go to the extra trouble of converting AC to DC? There are several reasons. First, most communications equipment includes semiconductors and other integrated circuitry that are specifically designed to operate with DC, such as:

- Telephone switches
- Microwave transmitters
- Fiber-optic transmitters
- Mobile radio and cellular systems

Another reason DC power is preferred for communications systems is its reliability advantage. Even the most advanced electrical grid can fail from time to time, and no one is immune to the possibility of power interruptions that may last for hours or days. When the outage occurs at a cell station, shutting down is not an option. So battery or fuel-cell backups are installed to allow continuous operation and these power sources produce DC power. This system is used for both cellular and conventional land-line telephone service, which is why you still get a dial tone even when your home's AC power is out.

DC power by the numbers

Communication equipment requires specific voltages of DC current. Most commonly, the requirements are positive 24 volts (+24V) and negative 48 volts (–48V). These high voltage values reduce their associated current and lighter current requirements allow for smaller and less expensive fuses, circuit breakers and cables.

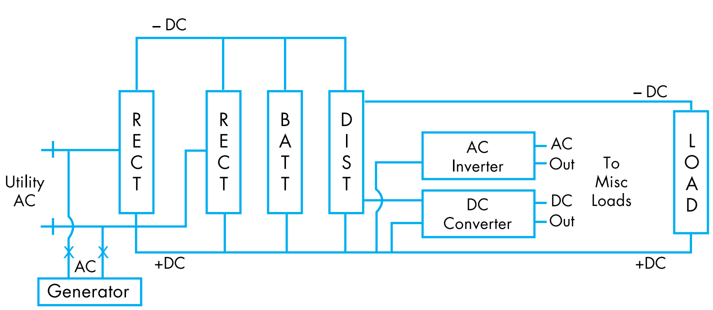
The +24V value evolved from the early mobile radio industry, back when equipment was designed to draw power from a +12V automobile battery or +24V truck battery, the same kinds of batteries used today.

Going beyond the basics

As mentioned above, the basic core components of a communication system's power connection are the rectifier, which converts AC current to usable DC current, and the batteries which assume the load when external power is interrupted. Once DC is online, however, we must consider the specific power needs, or loads, of different equipment. We need a means to distribute the correct voltages to each piece of equipment.

To make these adjustments, devices called DC-DC converters can modify the primary DC voltage to suit the needs of a piece of equipment that demands a different voltage. In the event that some equipment requires AC current, we can also include a device called an inverter, which changes DC back into AC. Because this all takes place behind the station's main rectifier, this reconverted AC power isn't subject to interruptions from the external power supply. A sample diagram showing all these components appears below (figure 9.2).

You may also notice an important new element appearing in this diagram: the generator. Generators supply AC power for the station's rectifiers if external power is interrupted. This keeps all systems operating and the batteries fully charged. There are several kinds of batteries and generators in common use. Selecting the right generator often depends on space, budget and operational expectations.



9.2: Block diagram of a basic telecommunications power system

Volt (V)
A measurement of electric potential difference between two points in a path. Voltage is sometimes referred to as "pressure," because it shares many characteristics with pressure in a water pipe.

The chemistry of batteries

At its most basic, a battery is an electro-chemical method of storing and releasing electrical energy. A battery contains chemicals that react with one another, producing DC electrical current as a byproduct. The specific chemicals and processes may vary—we will examine some common varieties below—but, on a fundamental level, all batteries operate on this core principle.

While the battery is receiving a charge from a fully operational system, it does not discharge any current. Rather, it consumes a small amount of DC from the power relayed by the rectifier. When this current is interrupted, natural processes kick in and the batteries discharge their stored DC power in accordance with the load placed on the circuit. Most importantly, this shift occurs seamlessly and leaves no interruption in current.

Reliable backup times usually range from two to eight hours, depending on the load. Since telecommunications providers must be able to specify expected operational times, choosing the best type and configuration of batteries is critical.

Lead-acid batteries

These are commonly used as backups for telecom power systems. They are highly compact relative to their output, and are the same kind you would find under the hood of your car. They are available in vented and valve-regulated forms (figure 9.3).

Flooded battery

VRLA battery

9.3: Vented (flooded) and valve-regulated (VRLA) batteries

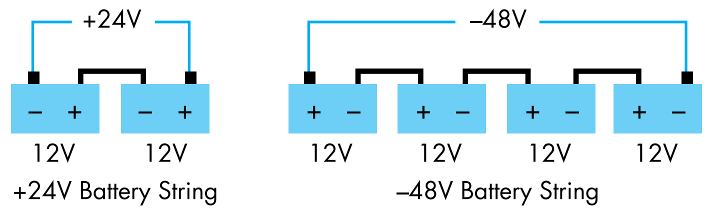
Vented (also known as **wet** or **flooded**) **batteries** are a mainstay of telecom central offices and switching centers. They maintain a charge for up to 20 years or longer. However, they demand a great deal of costly maintenance such as water treatment, spill containment and forced-air ventilation. These drawbacks make them less suited to remote cell base stations.

Valve-regulated lead acid batteries (VRLAs) are recombinant batteries, which means oxygen and hydrogen can recombine to prevent water loss. Because they don't need added water and can therefore be built in spill-proof containers with pressure relief valves, these are often called sealed lead-acid batteries. They are easier to ship, maintain and install, and cannot freeze like a flooded battery, making them the preferred choice for cell base station use.

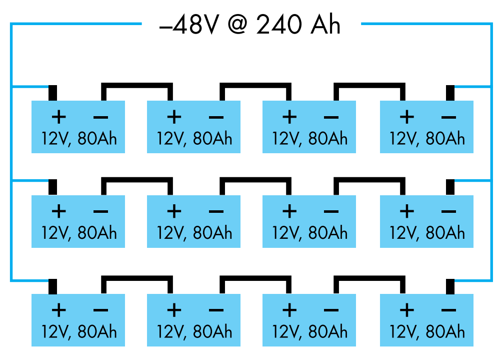
Battery cell configurations

Each battery is comprised of cells arrayed in electrical series. The number of cells used in a particular battery is determined by the overall required operating voltage and the voltage of each cell. For VRLA batteries, a standard voltage of 2V per cell is the norm so, to power a +24V system, 12 such cells must be connected in a series. Likewise, a –48V system requires 24 cells. Often, VRLA batteries are available in 12V blocks, like those seen in figure 9.4.

The arrangement of these batteries in series determines the voltage polarity. If each of the 12V batteries shown above is rated for 100 amp-hours, then each series string of batteries could be expected to produce 100 amps of current for one hour. Capacity is directly related to the size of the battery, but rather than spending more on larger batteries, we can achieve the same boost to capacity by adding more strings of batteries to the system in parallel as opposed to adding them in series. This option also provides safeguards against the failure of an individual battery, which would remove its string from the system altogether. By connecting in parallel, the spare capacity is already online and ready to maintain the current for its rated length of time. A diagram of sample parallel battery strings rated at 240 amp-hours, appears below. Note that if a battery failed in any of the three series strings, the remaining two strings would continue to supply steady power at 160 amp-hours (figure 9.5).



9.4: VRLA batteries configured in series for +24V and –48V applications



9.5: A multi-string battery configuration offering additional redundancy

This configuration also provides a convenient means of maintaining the batteries. Often, these strings will be installed with separate disconnection breakers, which make it easier to locate failures and isolate problems that could otherwise cripple the entire system.

Voltage polarity: positive (+) and negative (–) voltage

The + and – designations of +24V and –48V refer to which polarity of the battery circuit is measured; in terms of actual power produced, the distinction is meaningless.

Generators: the first line of defense

If batteries are the last line of defense against service interruption, generators are the first. Since batteries alone can only maintain operations for a few hours, longer AC service interruptions require a longer-term solution and that means generating our own power.

Unlike batteries, generators provide power by burning fuel. Like batteries, there are different types and configurations available. Which one you install depends on factors like space, cost and service expectations.

Since they operate outside the cell station's internal DC system, generators aren't considered part of that system. Because they supply the DC system's rectifiers with the AC they need, however, they're a vital link in assuring reliable operation. In the event the station must switch from external to generator-supplied AC power, an electrical device called a transfer switch shunts the load to the generator.

For stations with permanently installed standby generators, an automatic transfer switch (ATS) monitors external power levels and performs the changeover to generator power if the voltage drops below acceptable levels. View an example of AC generator. (Figure 9.6)

AC permanent genset

9.6: AC permanent generator

Generator fuel sources

You may have an emergency generator at home, or use one for electrical service in a remote location. Chances are that your generator runs on ordinary gasoline. Larger generators may also use compressed natural gas or diesel fuel, but the optimal generator for a DC system like a cellular base station is hydrogen fuel cell technology, for several good reasons.

Hydrogen fuel cells use proton electrolyte membrane (PEM) technology to generate DC power. We'll explore this later, but from a practical standpoint, hydrogen fuel cells offer several key advantages over their petroluem-fueled cousins.

Hydrogen fuel cells:

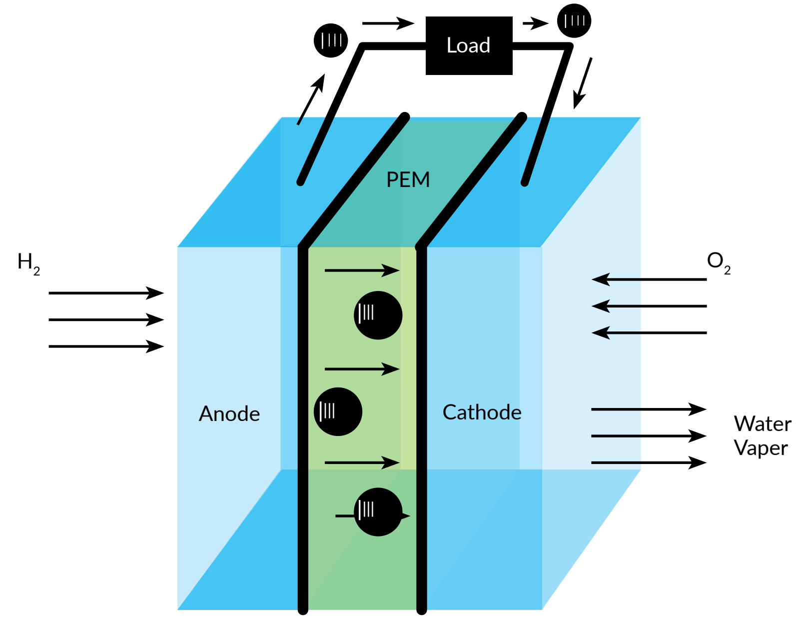
- Run on inexpensive, readily available hydrogen
- Produce very little heat, preventing damage to other components
- Offer higher efficiency than typical diesel generators
- Operate in ambient temperatures from –40°F to 122°F
- Are more compact than other fuel cell types
- Are quiet and non-polluting
- Have no moving parts, extending their operational life spans
- Require very short warm-up periods so they come online quickly

Generators in general, and hydrogen fuel cells in particular, can provide large amounts of steady, predictable power for extended periods of time.

The science of fuel cells

In a PEM fuel cell, hydrogen atoms are stripped of their negatively charged electrons at the anode end of the battery. This ionizes the hydrogen atoms, giving them a positive charge. The liberated electrons provide the actual DC to the connected equipment. Meanwhile, at the cathode end of the battery, oxygen combines with the hydrogen and electrons returning from the circuit, creating water (figure 9.7).

As long as the system is supplied with hydrogen and oxygen, the fuel cell will produce a predictable amount of current.



9.7: Basic operation of a hydrogen fuel cell

Hydrogen fuel cell installation

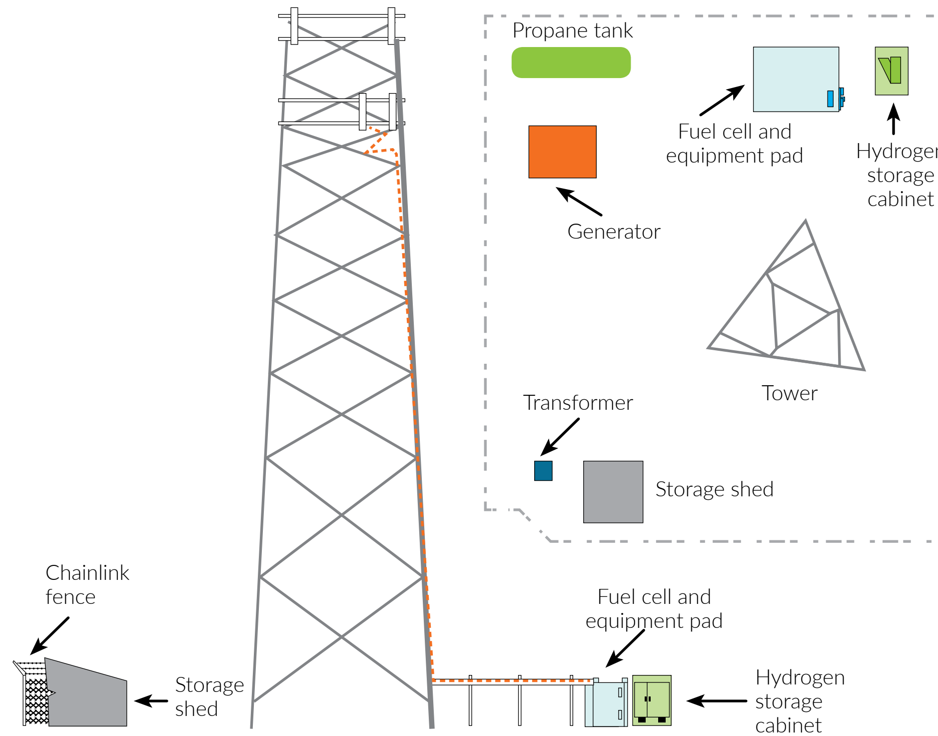
Hyrdogen fuel cell installations include three main components: hydrogen storage, a fuel cell stack and power module, and an integrated bridge battery. A typical layout is shown in figure 9.8, along with a view of an actual installation in figure 9.9.

Hydrogen storage

Like many liquid or gaseous fuels, hydrogen is stored in tanks. For a fuel cell deployment at a cellular base station, this storage would usually comprise 8 to 16 cylinders of compressed hydrogen.

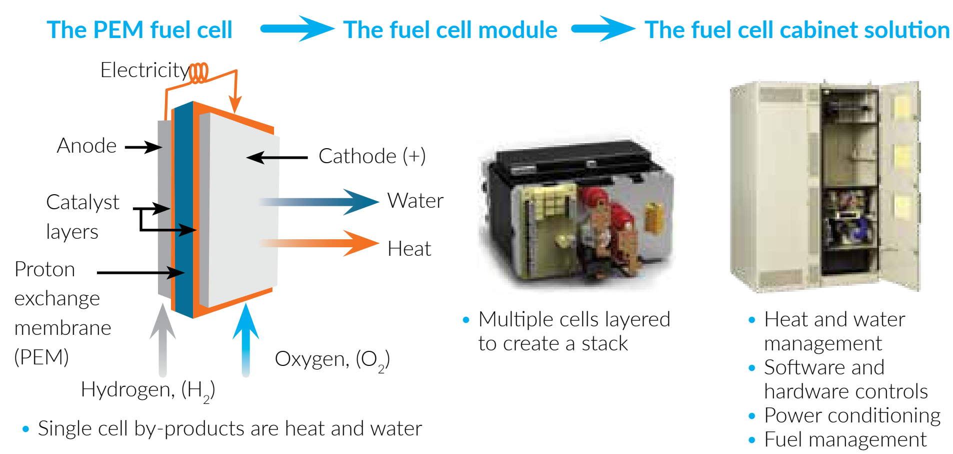
Fuel stack and power module

Because of the power demands of base station equipment, a single fuel cell cannot provide enough power by itself, so multiple cells, called a stack, are linked together in a fuel cell power module (figure 9.10). This linked arrangement is similar to the multiple battery configurations discussed earlier.



9.8: A typical layout for a base station's fuel cell power plant

9.9: An actual fuel cell and hydrogen storage cabinet installation



9.10: The connection between fuel cell, fuel cell stack and fuel cell power module

Bridge batteries

While hydrogen fuel cell generators warm up quickly and are ready for service shortly after an AC power interruption, there is a brief bridging period when batteries must carry the load alone. These integrated battery backups provide the necessary power to cover the brief time needed for a fuel cell to come online.

Fuel supply and maintenance

Hydrogen fuel cells are efficient, quiet, reliable and long lasting. But, like any generator, they require a supply of fuel to operate. When the hydrogen supply dwindles, an automatic alarm alerts the system's operator that fresh supplies are needed. To preserve hydrogen, fuel cells are designed to shut down once external AC power has been restored. They are then ready to engage the next time an interruption occurs.

With no moving internal parts to wear out and very little heat radiation, fuel cells require very infrequent maintenance, often amounting only to an annual inspection of their oxygen intake filters and radiator fluid levels.

Rectifiers: the AC-DC interface

Once beyond the external source of power, whether it's commercial AC electrical service or an AC generator, the rectifier is the core of the system's DC power distribution needs.

The rectifier is designed to provide an output DC voltage level that maintains the battery charge. This level is called float voltage, and it supplies the equipment load as well as a trickle charge to the battery. In the event of an AC power interruption, the rectifiers go offline and the batteries automatically kick in, providing the same level of power to the rest of the system. When external AC power is restored, the rectifiers re-engage and the batteries return to their trickle-charging state (figure 9.11).

In practical deployments, multiple rectifier modules are usually required to supply power for the station's load. Rectifier modules are connected in parallel, letting each one share an equal part of the load, a practice known as load sharing. With load sharing, operators can design in a degree of redundancy to guard against individual rectifier module failures.

9.11: External AC power on (float mode) and off (discharge mode)

How redundancy adds up to reliability

For a –48V application with 200 amps of load, an operator may choose to install five 50-amp rectifiers.

Why add a fifth, when four would provide the requisite 200 amps? To ensure N+1 redundancy. Arranging multiple rectifiers in parallel allows load sharing to even out and shift the load.

Choosing the right rectifier

The first consideration in deciding which rectifier will best suit a given installation is the kind of AC power it will receive. Switchmode rectifiers are the preferred choice for cell and microwave sites since they can support multiple AC inputs and have a broader operating range—from single-phase to three-phase inputs. This flexibility means fewer rectifiers are required, saving money, space and maintenance.

Another consideration is the required output voltage. As we've seen, the rectifier must be able to output the voltage required by the station's equipment, that is, +24V or –48V. The amount of current must also be sufficient to power all the loads, such as the radio, transmission equipment and battery backup.

83A Switchmode
6.3H x 3.4W x 11.8D

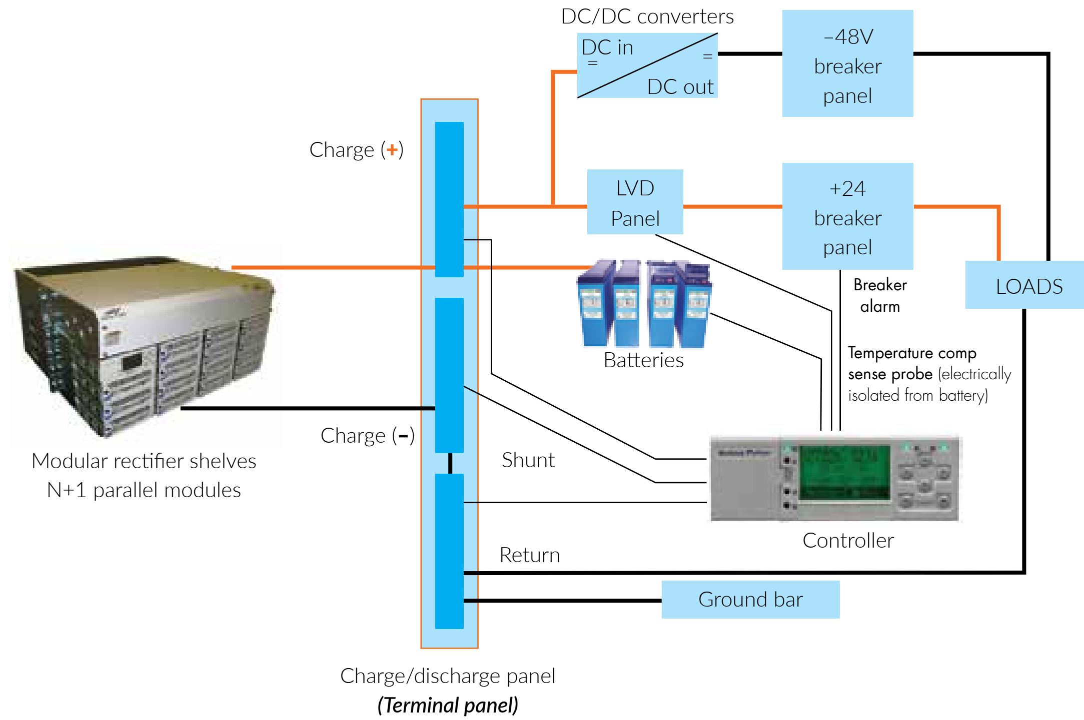
9.12: Example of a typical rectifier

Distributing the power

The rectifier is merely the first stage in the DC power system. Once converted, the power must be distributed to the many component loads within the system. As mentioned above, these loads include core elements like the radio, transmitter and battery backup, but they can also include secondary systems like lighting, security networks and HVAC systems (figure 9.13).

In the most complex installations there may be so many components that up to 80 circuit breakers are required to manage them.

The most visible parts of the distribution system are the fuses or circuit breakers, which safely distribute DC power from the rectifier to each individual load. Fuses and breakers are connected in series between the power system and their loads, protecting them from short circuits and damage from overload conditions. They also provide a safe, simple way to manually shut down individual components or batteries for service, maintenance or replacement.



9.13: A diagram of a typical +24V power distribution system

Images and illustration courtesy of GE.

Fuses vs. circuit breakers

While both fuses and breakers provide overcurrent protection, they do it in different ways. Fuses are designed to melt under unsafe currents, physically breaking the connection between the power source and the load. Circuit breakers have internal switches that pop to the "off" position under unsafe conditions, again providing a physical break in the circuit.

Sensitive wireless equipment requires "fast blow" fuses or short delay-curve breakers to provide the needed protection. Fuses are generally used for lower loads and offer the advantages of lower cost, greater flexibility and fast action. Circuit breakers are preferred for larger loads and do not require replacement every time they are tripped. Some typical examples are shown to the right (figure 9.14).

Because complex cell sites can require from 24 to 80 breakers of varying capacities, wireless carriers have adopted modular distribution structures that can accept a wide range of breaker sizes.

Surge protection

Typical variations in AC power are not the only threat to a cell site. Electrical events like lightning can also produce excessive voltages and currents, events known as electrical surges. Surge protection devices (SPDs) are incorporated to reduce the effects of these surges on sensitive electronics (figure 9.15).

An SPD features a non-linear voltage-current characteristic that reduces unsafe voltages by increasing the conducted current. In this case, a cell site's SPD operates on the same principle as a surge protector does in your home, safeguarding expensive electronics from lightning-induced surges.

9.14: Common types of telecom fuses and circuit breakers

9.15: Typical surge protector devices (SPDs); image courtesy of Raycap Corporation

Bus bar conductors

The cell site's distribution system is supported by the bus bar conductors, which physically connect the rectifiers to the batteries and DC loads. There are two bus bar connectors: the **charge bus** and **battery return bus.**

> The **charge bus** is a current-carrying conductor that connects the rectifier's output to the battery string. For instance, in a –48V system the negative rectifier lead would terminate on the charge bus along with the corresponding negative lead of the battery.
>
> The **battery return bus** provides a common return point for the loads connected to the power system. This common point is grounded to provide a low-impedance path for transients and noise, and offers a ground reference to all connected equipment.

The shunt

In a distribution system, a shunt is a low-resistance resistor designed to provide a specific voltage drop at a particular level of current. As the current passes through the shunt, it develops a small voltage proportional to the amount of that current. This voltage drop allows an operator to calculate the current flow in the system.

Battery disconnects

Battery disconnects are switches installed on a battery string that allow easy disconnection for maintenance or replacement. Some disconnects incorporate safety measures such as overcurrent fusing or breakers.

Load disconnects

Low-voltage disconnects (LVDs) are designed to respond to low voltage conditions in the circuit. Low-voltage load disconnects (LVLDs) can disconnect individual loads, while low-voltage battery disconnects (LVBDs) can disconnect a fully discharged battery.

LVDs serve three main protective functions:

1. They prevent damage to sensitive electronics caused by low-voltage (and hence, high-current) conditions
2. They prevent permanent damage to the battery from over-discharging
3. They prioritize which components are disconnected, and in which order, preserving limited function when necessary

Supervision, monitoring and control

Modern telecommunication power plants are equipped with electronic monitoring and control systems, generally called **controllers.** They keep track of system voltages, currents, temperatures and other key indicators. They also allow operators to make adjustments from a central monitoring point, usually on the power plant itself, on the distribution cabinet or in a rectifier slot (figure 9.16).

9.16: A system controller interface displaying voltage, amperage and alerts

With a modern controller, there is very little you can't learn about your cell site's power system performance.

This controller centralizes several key functions in a single, simplified interface, including:

Plant control. Control functions are extended from the supervisory panel to control other power system components. These panels communicate directly with the rectifiers, and in some cases can coordinate the sequenced restart of all rectifiers to prevent power surges during switchovers from external AC to a backup power source.

Manual equalizing. This allows a user to engage all rectifiers in equalize mode at once. This is useful for maintenance on VRLA batteries, equalizing cell voltage within a battery string.

High-voltage shutdown/overvoltage protection (HSVD/OVP). Controllers can automatically shut down rectifiers when DC output overvoltage conditions are detected, avoiding costly damage to load components.

Low-voltage disconnect (LVD). If a low voltage condition is detected in the backup batteries, the controller can open additional contacts to equalize voltage and close them again when levels equalize.

Battery temperature compensation. The controller can adjust rectifier output to meet the temperature-driven voltage needs of the batteries.

Charge current control. This feature limits the current flow to a battery when it begins recharging after a power interruption. By keeping the battery from recharging too quickly, it prevents overheating and prolongs life.

Battery diagnostics. The controller can estimate the "health" of the battery and predict how long it will provide power based on its charge status.

Alarm monitoring. The controller monitors critical functions like distribution and battery fuse alarms, rectifier failures, converter failures and so forth. It reports these alarms by way of network backhaul interfaces and LED indicators. Some units include audible alarms as well.

Status monitoring. The controller can measure and compare the battery charge to the system load via an external shunt.

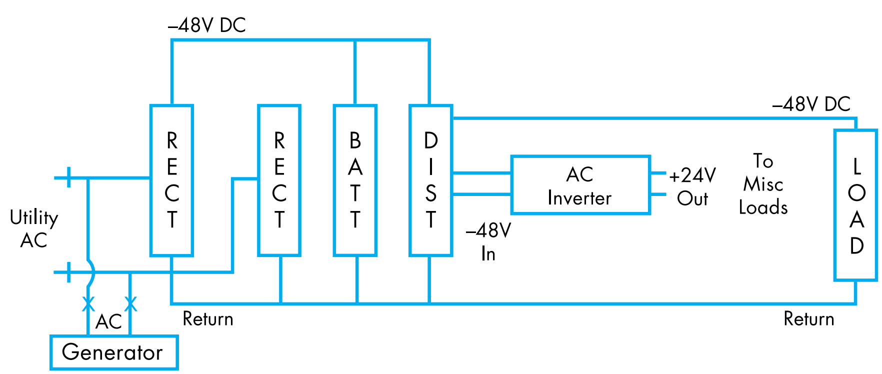
Plant history. Controllers can log power system details over a span of time, including such statistics as thermal performance of outdoor enclosures, battery cell states, or variations in AC input experienced by the rectifiers.

DC-DC power conversion

Some wireless sites require multiple DC voltage outputs, such as +24 VDC and –48 VDC. One solution is to install a second rectifier plant, but doing so comes with the burden of including a second battery backup array as well, which consumes considerable space and adds cost.

Another solution is to use a DC-DC converter system, an electronic power conversion device that changes a DC input voltage to a different DC output voltage. Below, you can see where a DC-DC converter system is connected in series between the main DC power system and the site's load (figure 9.17).

A DC-DC converter system actually consists of multiple DC-DC converters arranged in parallel. It may also incorporate many of the same functions as the primary DC power system, such as distribution. It also has dedicated fuses or circuit breakers, isolating it from the rest of the system.



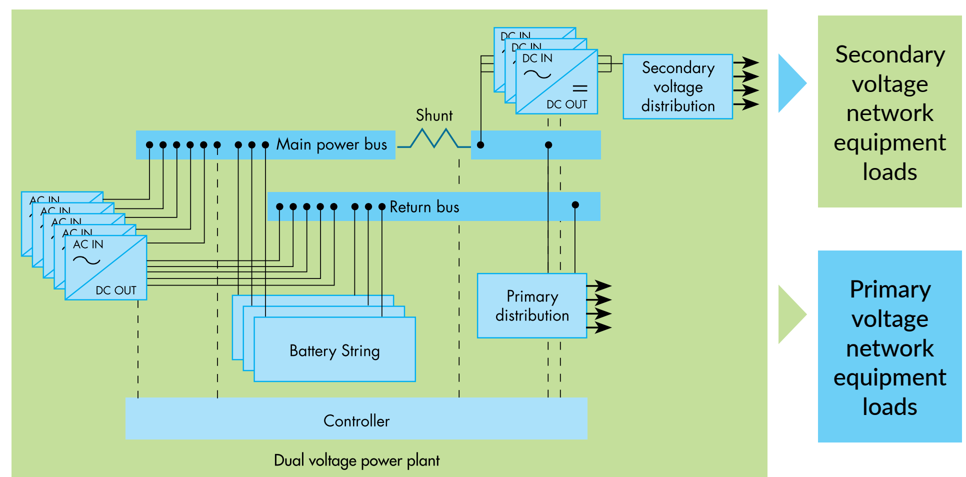
9.17: A DC-DC converter system connected in series to a cell site's power system

Since a DC-DC converter system does not have an associated battery connected to its output, it isn't bound by a battery system's requirement for precise output voltage. However, since it is necessarily energized by the primary DC power system, that demand must be figured into the power system's initial design.

Dual-voltage power plant using DC-DC converters

Ordinarily, a DC power plant's rectifiers and batteries supply consistent power for a single voltage requirement. If two requirements exist at the site and the demand is heavily skewed toward one voltage or the other—either predominantly +24V or –48V—the secondary voltage may be supplied through the addition of a DC-DC converter system.

Because the conversion takes place between the rectifiers/batteries and the load, the secondary voltage will still receive all the backup support of the primary voltage in the event of external AC service interruption—and only one set of backup batteries is required (figure 9.18).



9.18: Supporting two voltages at a single site using one power plant and converters

Integrated power systems
Space-saving combinations of related components, built into a single device for easy installation.

Advantages of converting voltage

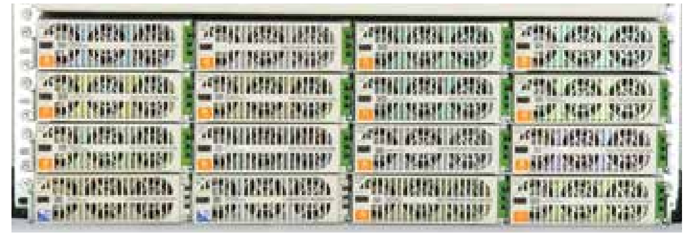
Modern DC-DC converters are essentially "plug and play" devices that are designed to fit in the racks alongside rectifiers and other converters (figure 9.19).

This approach offers communications providers the greatest flexibility in adopting next-generation technology, offering new services while maintaining older standards. As the deployment of the newer technology grows, additional converters can be added to the system to increase the secondary voltage's share of the power supply. It should be noted, however, that doing so may require upgrading the rectifier capacity as well, while making sure to maintain the usual redundancy margin.

Disadvantages of converting voltage

On the downside, converting to a given voltage is inherently less efficient than drawing that voltage directly from the rectifiers, so losses increase as more and more DC power is converted away from the primary voltage.

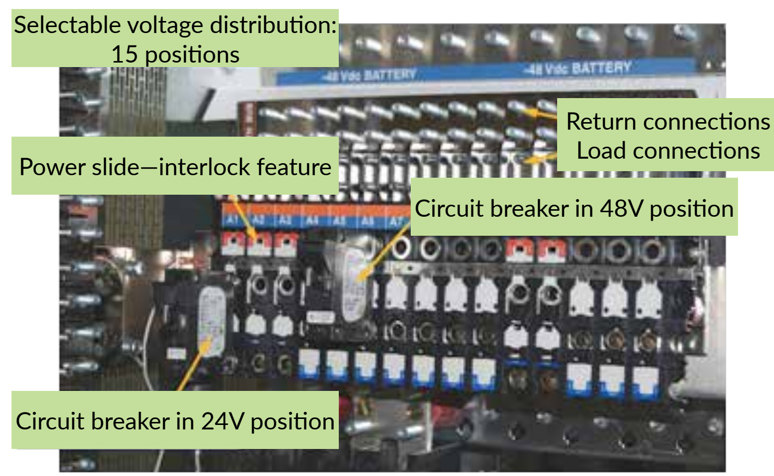
Also, many traditional power plants cannot support the direct addition of converters to their systems. To draw two voltages in these instances, a separate converter plant must be installed. The converters draw power from the existing DC power plant via fuse or breaker positions in the distribution system, just like any other load device. This reduces the number of available distributions for the primary voltage equipment at the site.



9.19: Converters and rectifiers occupying adjacent power shelf slots

Mapping the positions

Since a single power plant can generate varying amounts of both primary and secondary voltages, the need arises to assign numbers to the distribution positions of each voltage. A selectable voltage distribution panel makes this organization possible (figure 9.20).



9.20: A selectable voltage distribution panel, showing both +24V and –48V applications

Integrated power systems

So far, we have focused on the individual components that comprise a cell site's power system. With so many components, you can imagine how quickly the space limitations of a site's shelter or cabinet become an obstacle.

To address these space limits, **CommScope** produces *integrated power systems* with several components built into a single device, and suited for installation in a single rack. This approach is increasingly common in modern cell sites.

A typical integrated cell site power system includes one or more shelves of rectifiers along with one or more shelves of DC-DC converters. This integrates power conversion and power distribution functions, connecting them with bus conductors. The distribution system contains an integrated DC bus, fuses or breakers and cabling tie-downs to distribute power to the load (figure 9.21).

Cell site power requirements range from 100 amps to several hundred amps of primary DC power. In +24V applications, these systems are configured to deliver 1,000 to 1,200 amps of primary power; –48V applications, about 600 amps. This may seem like a great deal of capacity, but the actual power consumption is typically far less than the system's theoretical capacity.

Since integrated power systems feature modular design, additional power can be added simply by plugging an additional rectifier into a vacant rack slot. Likewise, if there are secondary loads that use different voltages such as adding a +24V radio to a –48V system then DC-DC converters can be added to open slots to accommodate those needs. This is particularly useful in an age where radio technologies evolve at a rapid pace.

DC-AC inverter

Some of the equipment operating at a cell site may require AC current from battery backup supplies. Since the entire system is built around DC power, a DC-AC inverter is needed to provide the necessary AC voltage (figure 9.22).

There are two basic types of inverters:

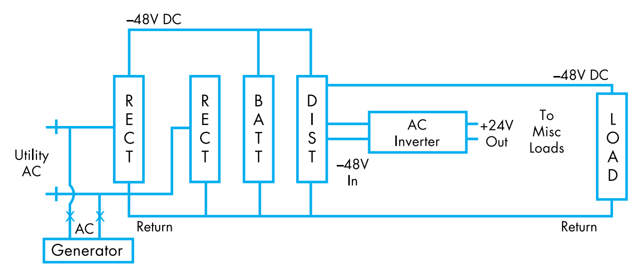
Offline inverters feature an AC input and an AC output with a standby DC line connection available. This is the type generally used in cell site applications.

Online inverters feature a DC input and an AC output with an optional AC standby line available.

Like DC-DC converters, the input for a DC-AC inverter is supplied by the primary power plant. Like converters and rectifiers, inverters are often installed and configured for redundancy. A static switch maintains equalized voltage to the load by switching automatically between external AC power and the inverter's AC power. This switching is done instantaneously, assuring no interruption in operation.

Along with the static switch, many systems also include a maintenance bypass switching panel in an inverter installation, which allows an operator to power down an inverter for servicing or replacement without disturbing the system's load. During this power-down time, however, the system load is entirely dependent upon external AC power.

9.21: An integrated rectifier, DC distribution and controller power system

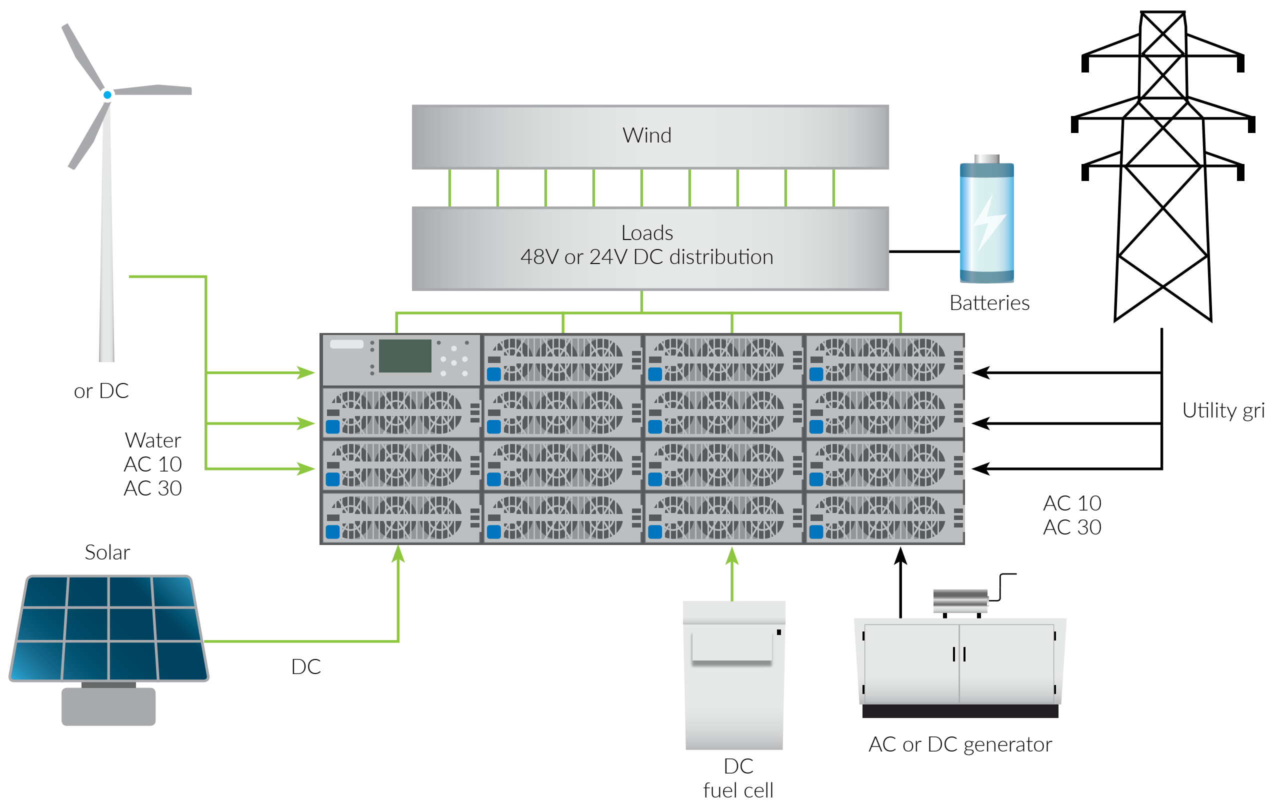


9.22: A DC-DC converter system connected in series to a cell site's power system

Remote radio head (RRH)
A recent design advance in base station architecture that separates a cell site base station's RF and baseband functions for improved efficiency.

AC power sourcing flexibility

With ever-increasing utility costs, the ability to combine power from renewable sources with utility power is another aspect of power flexibility. To address this, some rectifiers can accept AC power from attached solar panels or wind turbines just as easily as they can draw it from the utility's transmission lines. An illustration of this flexibility is shown below (figure 9.23).



9.23: Power source flexibility lets rectifiers draw from conventional or renewable sources

Architectural improvements to power management

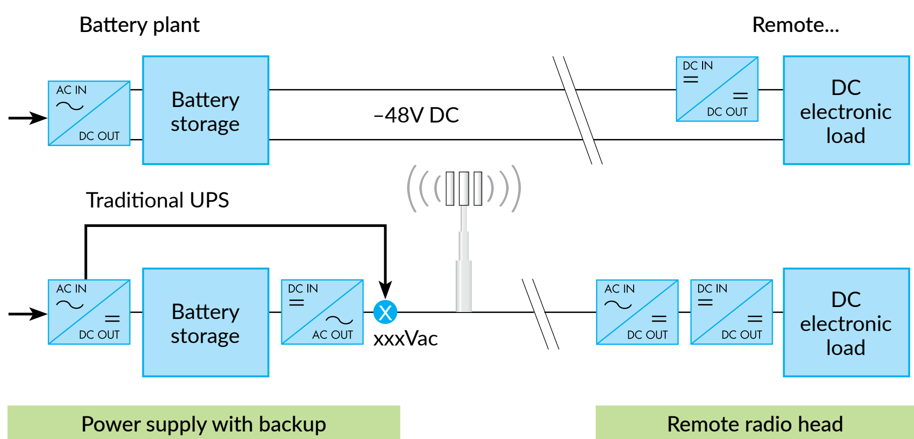
Significant power losses occur as a signal moves from the radio transmission equipment in a cell site's base station shelter to the antenna up on the tower. These losses are a natural consequence of traversing long stretches of coaxial cable. However, the simple architectural change of moving the transmitter and amplifier—known collectively as the radio head—from the shelter to the tower eliminates these losses and reduces power requirements. This design is called the remote radio head (RRH).

The baseband equipment remains on the ground and external AC power still enters at the cabinet or shelter. But with the transmitter amplifier mounted adjacent to the antenna on the tower, more space is freed up and less heat management is required.

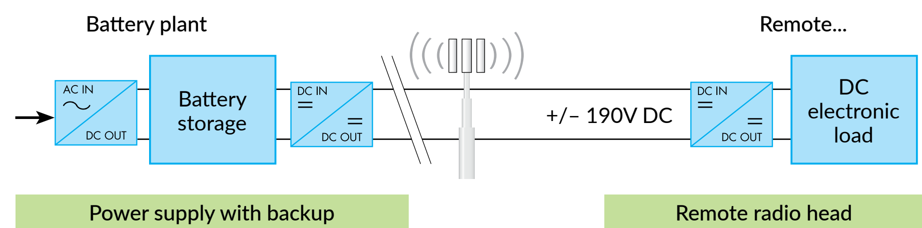
Because of its exposed location, the tower top is not suitable for the battery backups, but other RRH equipment can be easily sealed against the elements. Instead of coaxial cable running up the tower, now only power transmission lines are needed. Below are two possible methods of providing power to the RRH (figure 9.24).

As useful as this design is, it also introduces new challenges. For instance, since the battery backup is now located far away from the critical components in the RRH, a heavier gauge of power transmission line is needed unless the power is converted to a higher voltage down at ground level and then converted back to the needed voltage (+24V or −48V) at the RRH itself.

This arrangement sometimes uses "line power" equipment, which is now available for these applications. With line power, the ground-level voltage is increased to +/−190 V DC, reducing the current and thereby reducing transmission loss (figure 9.25).



9.24: DC powering options for remote radio heads (RRHs)



9.25: Line power voltage conversion used for an RRH application

Cell site power system configurations

Different cell sites store their power equipment in different ways. Some sites have equipment shelters at the base of the cell tower. Inside these climate-controlled enclosures, equipment is mounted in equipment racks, with an integrated power system in one rack and battery strings in another, and radio equipment in still another.

Other sites place integrated compact equipment in outside plant (OSP) cabinets. This approach offers less space and fewer opportunities for environmental management, so only components specifically designed for OSP cabinet environments can be installed. It is common practice to keep power and radio systems in separate cabinets. Because of their size, often batteries will have a dedicated cabinet as well. A few examples of OSP cabinets are shown in figure 9.26 and 9.27.

Keeping the power and communication flowing

A lot of thought, planning and effort is required to deliver and support our always-on, 24/7 world of communications. When power outages occur, as they inevitably do, it falls to forward-thinking engineers and companies like **CommScope** to put effective, reliable contingencies in place.

Many of the same systems that keep your home electronics in good working order like battery backups, circuit breakers, DC converters and surge protectors also keep our national cellular backbone in a state of constant readiness.

Interruptions in power shouldn't mean interruptions in our lives, and with the technology and expertise of **CommScope** and our partners in the communications industry, they don't have to.

9.26: Integrated cell site battery only cabinet

9.27: Integrated cell site power and battery cabinet

Chapter 9 summary

Powering wireless networks

- DC vs. AC power
- Cell site equipment requires DC power
- Rectifiers convert AC to DC

Batteries

- Lead-acid batteries are available in flooded and valve-regulated versions
- Backup systems built of batteries stringed in series and in parallel

Generators

- On-site power generation
- Hydrogen fuel cells

Distribution

- Fuses, circuit breakers
- Surge protectors
- Shunts
- Battery and load disconnects

Integrated power systems

- Combine multiple elements in one device

New efficiencies

- Dual-voltage power plants
- Remote radio heads
- "Line power" voltage conversion

Chapter 10

Successfully planning against failure:

Reliability in wireless systems

It's simply a fact of life that items left out in the elements will become more susceptible to problems as a result of such exposure. Outdoor furniture ages more quickly than indoor furniture, the car parked at the curb shows more wear than the car kept in the garage. As a matter of necessity, a home's exterior paint will need refreshing more often than its interior. The elements, as a rule, are harsh.

Planning for environmental punishment is also a key concern for cell site operators, as new efficiencies that wring more work from every watt often mean placing components farther out into the network, and that means placing them outdoors, high on antenna towers. The same degrading effects that peel a house's paint work relentlessly against the sensitive electronics that drive modern cellular communications.

The precise balancing act of increased component failure rates against operational efficiencies has led to a revolution in how cell towers and cell systems are developed and built.

CommScope is at the forefront of this new network architecture and its impact on reliability. We offer the tools and expertise to help operators maximize redundancy, improve weatherizing and plan for system component failure and systems all over the world.

Reliability
The probability of a device working correctly over a defined length of time, operating under specified conditions.

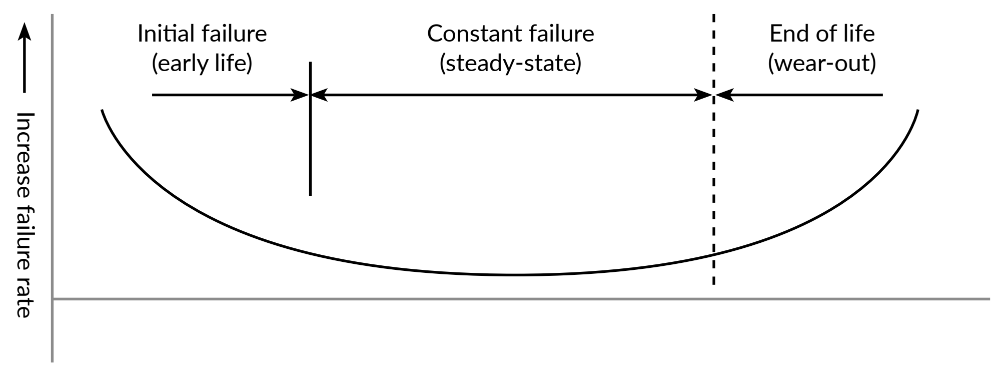
Reliability, objectively defined

In everyday conversation, reliability usually refers to your experience with a device or service. It's somewhat subjective in that no two people have exactly the same experience, and they don't react in the same way when a problem does occur.

For instance, your home Internet service may occasionally go down for a few minutes in the middle of the night, but since you're not using the Internet when it happens, you would refer to your service as highly reliable even though it occasionally fails. Another person might need a stable connection during a particular time of day and experience an Internet outage during that critical moment. Even though the interruption may last only seconds, that person would describe his connection as unreliable.

In engineering terms, however, reliability takes on an entirely new meaning. It has an objective, empirical value based on study, analytics and calculation. In this sense, reliability is defined as the probability that a product or service will perform as it should at any given time, under specific conditions. In engineering, "failure" is something to be anticipated, controlled and compensated for via system redundancy.

Generally, reliability rates can be defined with a classic bathtub curve, so named for its bowl-like shape (figure 10.1). As you can see, it predicts higher failure rates at the beginning and ending of a device's life cycle. For any given device, this graph provides a general guide as to its rate of failure—decreasing initially, and increasing during end of life.



10.1: The reliability "bathtub curve," showing the failure rate over the operational life of a device

The three stages of component life introduce three common causes of failure:

1. **Early-life initial failure** may be due to manufacturing problems, incorrect installation or damage during shipping.
2. **Steady-state constant failure** indicates random failure as a normal function of operation. This is the stage we are most concerned with in this chapter.
3. **End-of-life wear-out failure** occurs when fatigue, corrosion or other factors accumulate to the point where failure becomes more and more likely.

Determining when a device's end-of-life stage occurs depends on complex computations. For example, one must take into account known life expectancy of the device's main components, such as motors and fans with moving parts that are eventually subject to mechanical wear.

Similarly, electronic components also have life expectancies. For example, electrolytic capacitors used in wireless electronics are subject to degradation from high temperatures and AC ripple currents.

Quantitative reliability predictions

As you might expect from a complex wireless communications system, predicting likelihood of failure is a complicated process, but a necessary one. There are several methods:

1. Collection of empirical field data from customers
2. Accelerated life testing data
3. Prediction models based on "parts count" method
4. System availability models for large systems with internal redundancy

Each method offers different advantages. The "parts count" method, for instance, is particularly useful for new product designs, even before the product moves beyond its design stages. This method applies established life cycle information for the components used in the design—the steady-state failure rates indicated in figure 10.2—to create an aggregated model of potential failures.

This computation relies on industry software reliability prediction tools such as Telcordia SR-332 Reliability Procedure for Electronic Equipment. It adds up individual component failure rates and applies designer-specified multipliers accounting for specific temperature, electrical stress, production quality and environmental conditions to yield a final, steady-state failure rate for the component. The various stress parameters are:

- Stress factor for operation is de-rated from specified limits
- Temperature factor (often adjusted up or down from a reference point of 40°C)
- Quality factor accounting for supplier and process controls
- Environmental factor accounting for indoor vs. outdoor conditions

From such prediction tools, a designer can compute a predicted failure rate with a 90 percent or greater confidence limit, which means at least a 9-out-of-10 chance that the actual failure rate will be no higher than predicted. These estimates usually reflect conservative numbers, making them highly reliable predictors.

Stress factors

Of the several stress parameters, perhaps the most critical factors in predicting reliability in the wireless communications industry are temperature and environmental stress.

Temperature factor, more specifically operating temperature, is the sum of the ambient temperature and the temperature of the heat produced by the component itself. In practice, a 10°C increase in operating temperature can double the likely failure rate. Likewise, reducing the temperature by a similar amount can reduce predicted failure rates by up to 50 percent.

Environmental factor is just as important as a predictive element. For example, an outdoor environment introduces a multiplier of 1.5 to 2.0, depending on the outdoor application. This factor accounts for variations in temperature, vibration and other environmental variables in an uncontrolled outdoor deployment versus the same equipment in a climate-controlled enclosure. Recent data suggest that a 1.5 factor is typical for outdoor wireless equipment such as tower-mounted antennas and remote radio head (RRH) equipment. Much of this data was collected by monitored RRHs.

Water ingress protection starts with the careful analysis of points of ingress, design considerations for protection of critical RF connection points, formulation of condensation and management of condensation. Addressing each element often means tradeoffs between cost and efficiency in the design.

The final product of the reliability prediction tool includes detailed, part-by-part information such as that shown on the right (table 10.2).

Part number	Category	Unit FR (FITs)	Quantity	90% CL Failure rate (FITs)	Ref des
7094037	Capacitor	0.21	1	0.26	C37
7131706	Resistor	0.57	15	9.42	R3, R44, R6, R20
7131748	Resistor	0.57	3	2.10	R150, R151, R152
7131797	Resistor	0.57	9	5.80	R1022, R243
7144735	Capacitor	0.21	10	2.24	C152, C162
7144739	Capacitor	0.21	2	0.49	C58, C740
7164258	Miscellaneous	3.80	5	25.82	AT1, AT2
7165048	Resistor	0.57	1	0.80	R126
7500917	Resistor	0.57	1	0.80	R23
7501483	Resistor	0.57	1	0.80	R135
7512949	Capacitor	0.21	1	0.26	C1053
7541771	Integrated circuit	6.02	2	16.66	U1007, U1011
7563383	Integrated circuit	6.02	1	9.31	U1017

10.2: Example of a component reliability table

Measuring reliability

As mentioned above, reliability is the probability that a device will perform correctly under defined operational conditions over a specific span of time. But supporting this general definition are several practical ways of measuring reliability in real-world applications.

Mean time between failure (MTBF) is the time between two consecutive failures. This is the most common definition for reliability. MTBF is expressed as the inverse of the failure rate.

MTBF = 1 / Failure rate = 109 / FITs.

Mean time to repair (MTTR), sometimes called mean time to restore, is the time needed to repair or replace a failed component and restore its function. This includes procurement and travel time, so the figure is comprehensive in its scope.

Availability (A) is the percentage of time the system as a whole operates normally. When someone refers to "4 nines of reliability," they mean "99.99% uptime" (table 10.3). Availability is a function not only of how often a component fails, but also how long it takes to restore service when it does fail, so it figures in both MTBF and MTTR.

A = MTBF / [MTBF + MTTR]

When describing the reliability of an entire system, availability is a more useful measurement. That's because redundancies built into the design may tolerate some individual failures without seriously compromising the function of the system as a whole.

Unavailability (U) is the flipside of availability, in that it expresses the percentage of time a system is not working properly. Also, like availability, it can be calculated as a function of MTBF and MTTR.

U = MTTR / [MTBF + MTTR]

As you may expect, A + U always equals 100%.

Downtime (DT) is derived from unavailability and expressed as the average amount of time per year the system will be in an unavailable state. Since it measures failures that often last only minutes, and expresses them as a percentage of a full year, we simply multiply the unavailability percentage by the number of minutes in a year, or 525,600.

DT = U x 525,600

To illustrate, consider a system with 99.99% availability, or "4 nines." That means its mathematical value is .9999, resulting in a U value of .0001. Multiplying .0001 by 525,600 yields an expected annual downtime of 52.5 minutes per year, or less than a full hour. This is a key indicator in overall service quality (table 10.3).

Percent availability	Number of nines	Downtime (minutes/ year)	Service quality level
99%	2-Nines	5,000 m/y	Moderate
99.9%	3-Nines	500 m/y	Well managed
99.99%	4-Nines	50 m/y	High availability
99.999%	5-Nines	5 m/y	Very high availability

10.3: Service quality measured by uptime; more nines mean more availability

Failures in time (FITs)
The number of expected component failures per billion operating hours.

Availability on a systemwide scale

Because of the vast number of components that make up a wireless communications system—each with their own failure rates, redundancies and importance to overall operation of that system—predicting long-term performance of the system as a whole can be quite a challenge.

From a design standpoint, cost constraints make it impossible to build components that are not subject to some degree of failure. Therefore, the design must incorporate redundant subsystems to avoid complete system unavailability due to any single component's failure. Properly implemented, these subsystems will allow the system to continue functioning at full performance, even in its degraded state, until repairs can be economically performed on the failed component.

Budgeting for failure

Dividing a system's functionality into subsystems allows a "reliability budget" to emerge. By breaking down the complex whole into manageable segments, subsystem reliability can be more easily modeled based on its parts count or by another appropriate method. Then, the likelihood of failure of the entire subsystem can be modeled to learn its effect on the overall function of the system itself.

In a practical example, consider the mass of electronic components mounted atop a cell site tower. The system can be broken down into subsystems involved in the transmit path, the receive path, the power system and other related functions. Each of these will have a maximum allowable failure rate assigned based on its importance to the operation of the system. So the site's designers can plan accordingly, the overall reliability budget is split up and allocated where it is needed most.

In practical applications, these models are more concerned with the functioning state of a system or subsystem, rather than with the actual hardware or software itself. At this level of planning, MTBF and MTTR become more meaningful descriptors of reliability than failure rate alone.

Failure mode, effects and analysis (FMEA)

Given enough time, component failure is a certainty. Where and when it occurs, however, is a variable that must be modeled to be predicted. That means a lot of what-if scenarios, not only of component failure but the effect of that failure on its subsystem and the effect of that subsystem on the system as a whole. For this kind of analysis, failure mode, effects and analysis (FMEA) is a simple, table-based method of measuring these variables together.

The FMEA for a particular system lists each failure mode and its effect on overall system performance. Failures that result in total loss of service are combined to calculate the system's total availability, while failures that cause only minor effects on service are combined to calculate the system's partial availability.

Fault-tolerant design

Redundancy is the key to boosting availability within a system without requiring the subsystems to be more reliable themselves. Redundancy schemes vary by application, but they all have one thing in common: on-demand access to a device or service that can assume the function of a failed device until it can be repaired or replaced. Sometimes this includes a spare component; other times it means shifting load to other systems. Common redundancy schemes include:

- **Active/hot standby,** a spare component built into the system that operates all the time and can assume more load when needed due to primary component failure
- **Active/cold standby,** a spare component built into the system, which only comes online in the event of failure, with a possible interruption in service
- **1 + 1 load sharing,** providing two active routes for communications so one will be available in the event that component failure causes an outage in the other
- **N+1 load sharing,** providing a standby alternate route for communications to assume the load in the event that component failure causes an outage in any of the other routes

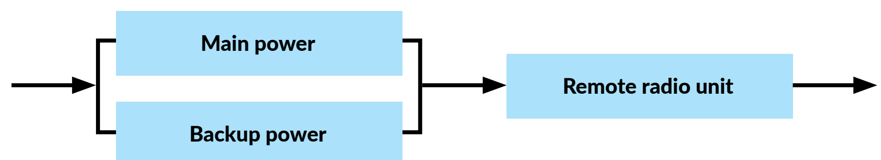
The downside of adding redundancy is increased cost. Therefore, redundancy should be added in circumstances where benefits outweigh costs.

The reliability block diagrams

Another widely used approach to measuring system reliability is the reliability block diagram (RBD). Unlike the lists of the FMEA table, it graphically shows the interconnections between subsystems on a conceptual level and how redundancy measures are integrated. Also, unlike the FMEA table, these element "blocks" are described purely by function, not by individual component; the system's reliability depends on how these blocks are connected. Arrows represent the direction of information flow, but may not necessarily correspond to the physical direction of current in the system.

How the RBD shapes up depends on the kind of system architecture under consideration. A typical architecture may include both redundant and non-redundant subsystems, as shown in figure 10.4.

An RBD is extremely useful in predicting system reliability, but it does have disadvantages. The main limitation is its static nature: it can only predict individual failures without accounting for cascading effects throughout the system as it continues to operate in a degraded state.



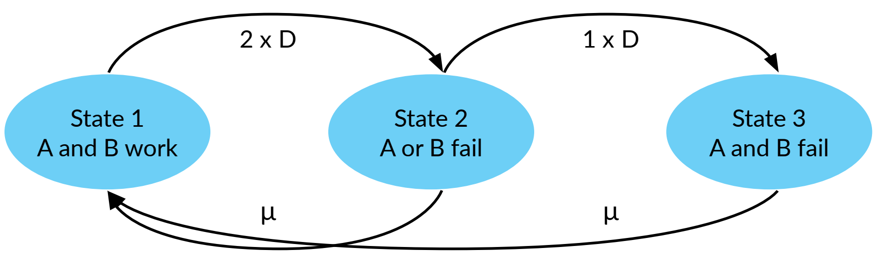
10.4: A simple RBD showing redundant power and non-redundant radio unit

State transition diagram (Markov Model)

In non-redundant systems, there are two states of being: working and not working. Transitions between these two states are defined by failure rates (1/MTBF) and repair rates (1/MTTR). Between these two measurements, availability can be easily determined.

However, more complex and more fault-tolerant systems have many levels of operational efficiency. We have referred to systems operating in degraded states, or a state of partial failure. To measure the reliability of these complex systems, the Markov Model defines all possible degrees of a system's operation and maps every state transition involved in making those states occur.

To illustrate, consider a simple system with two subsystems, A and B, each with the same failure rate (figure 10.5). As you can see, there are three possible operating states: fully operational, partially degraded and complete unavailability.



10.5: A basic Markov Model describing the three possible states for a two-subsystem design

The arrows indicate potential failure and repair transitions between states with the failure and repair rates for each. Different failure rates among subsystems naturally introduce additional variables, but the computations remain the same.

Markov Models can account for multiple combinations of failure conditions and the effect each has on system performance. This offers a better view of the comparative severity of different subsystem failures and what kind of degraded performance can be expected.

Markov Models are very useful in calculating the cost/benefit analysis of steps designed to reduce failure rates at various places within a system—essentially putting a "time and trouble" cost on any possible subsystem failure, which is particularly valuable when considering how difficult it is to service tower-mounted wireless communications equipment. It can also inform design decisions at the planning stage, taking into account accessibility factors early in the process. The downside to the Markov Model, however, is that it cannot assign a single MTBF value or failure rate to the system as a whole.

Reliability factors

Now that we are able to determine system reliability by multiple methods, we can examine what can be done to improve that reliability. These measures start in the design phase and carry through to installation and maintenance practices.

Product complexity is a primary factor to consider. Simply put, adding more components means adding more opportunities for failure. Take the integrated remote radio head (RRH) (figure 10.6).

10.6: A compact, tower-mounted remote radio head

With thousands of electronic parts built into a single device mounted in an outdoor environment, the predicted failure rate may be as high as 5 percent per year. This rate takes into account the ambient temperature, internal temperature and the RRH's heat dissipation features, as defined by Telcordia SR-322 software. Reducing the number of components in this or any device will directly increase its reliability.

Redundant hardware improves reliability by increasing the number of states in which the system may operate, adding flexibility to address service levels and repair schedules. However, redundant hardware will not reduce maintenance costs and it requires a greater up-front investment.

Heat dissipation is vital to the long-term reliability of any electronic system or subsystem, whether mounted atop a tower or located in a ground enclosure. For instance, a 60-watt amplifier may generate an internal temperature rise of 25°C to 30°C, which, when added to an ambient temperature of 25°C, yields up to 55°C of heat, exceeding the default operating temperature of 40°C found in the Telcordia SR-322. Recall that reducing operating temperature by just 10°C may reduce failure rates by 50 percent.

Thermal limitations relate to how heat dissipation is handled in a device. In the example of the RRH, front- and rear-mounted heat sinks arrayed in fins dissipate internal temperature rise into the air. The larger the fins, the more heat can be transmitted away. Limitations appear in the form of mounting orientation, available space on the mount and the physical size of the RRH itself.

Environmental issues are a key factor when dealing with electronics mounted outdoors atop a cell tower. Temperature variations, moisture, lightning strikes and other local conditions all play a part in how reliability is measured and improved. Each consideration should be thoroughly qualification tested and take into account prevailing industry standards.

Thermal design considerations

- Robust margins for thermal tolerance
- Design to conform to outdoor cabinet specifications
- Integrated thermal protection against over-thermal conditions

Mechanical considerations

- Resistance to high winds and vibrations on rigid mounting
- Accommodation of expansion and contraction
- Mechanical change-induced drift compensation

Atmospheric considerations

- Resistance to water infiltration
- Resistance to corrosion, fading and peeling
- Connectors, seals and gasket design
- Proper lightning mitigation (shielding and grounding)

Installation practices are just as important as design factors when it comes to ensuring reliability. As discussed in chapter two, it's vitally important to work with a competent and experienced cell site services company with well-documented safety records and tower climb-certified technicians to handle both mechanical and electrical services.

Qualified technicians will reduce the chances of improper lightning protection, poor connections, mishandled feeder cable and weatherproofing problems. In the long run, maintenance and troubleshooting are much easier and less disruptive to your network when trained professionals handle your work.

Reliability testing

A number of reliability test programs are designed to improve product reliability from early design prototype to deployment. Such tests include the following.

Design verification testing (DVT)

Products are tested to electrical and mechanical specifications contained in their product specifications. Testing includes, but is not limited to:

	Temperature and humidity exposure	
	Antennas/RF components	Outdoor cabinets
Cold exposure	Test per IEC 60068-2-1 at -40°C for 24 hr.	Test to -40°C per GR-487-CORE.
Heat exposure	IEC 60068-2-2 at +70°C for 24 hr.	Test to +46°C per GR-487-CORE.
Temperature cycling	IEC 600068-2-14 cycling between -40°C and 70°C for 96 hrs.; dwell times at limits shall be 1 hr. past chamber equilibrium and transition times between limits shall be less than 2 hrs.	Test from -40°C to +50°C per GR-487-CORE.
Damp heat (humidity)	Test per IEC 600068-2-30, Test Db; one 24-hr. cycle; 9 hr. at 25°C / 95% RH and 9 hr. at 40°C / 90% RH with 3-hr. ramp transitions.	Perform 7-day temperature/humidity cycling per GR-487-CORE for outdoor cabinets.

	Corrosion (salt mist)	
	Antennas/RF components	Outdoor cabinets
Continuous exposure	IEC 60068-2-11 Test Ka (ASTM B117) for a minimum of 720 hrs at 35°C with a salt mist concentration of 5 wt% NaCl	720 hrs. per ASTM B117 and GR-487-CORE
Cyclic exposure	IEC 60068-2-52 Test Kb (Severity Level 4 – 2 cycles) at 35°C with a salt mist concentration of 5 wt% NaCl	

	Ingress protection	
	Antennas/RF components	Outdoor cabinets
Water ingress	IEC 529; for IP67 mated connectors: 0.5-hr. immersion under 1 meter of water (9.78 kPa at 25°C). (Unless sand & dust tests are required, physical ingress rating is inferred from design and water ingress rating).	
Sand and dust ingress	IEC 60068-2-68, or per Telcordia GR-487-CORE section 3.28.4. Enclosure door(s) opened and closed 50 times before exposure and dust collectors (consisting of 1.3 cm thick, 2.5 cm X 2.5 cm black conductive, high-density polyurethane foam pads) placed inside. 0.9kg (2 lbs) of simulated dust (consisting of 325 mesh white hydrated alumina silicate, or equivalent) is blown into the enclosure at minimum velocity of 27 m/sec (60 mph) for 1 hr. The foam collectors are then removed and visually inspected for dust accumulation.	Telcordia GR-487-CORE section 3.28.4. Enclosure door(s) opened and closed 50 times before exposure and dust collectors (consisting of 1.3 cm thick, 2.5 cm X 2.5 cm black conductive, high-density polyurethane foam pads) placed inside. 0.9kg (2 lbs) of simulated dust (consisting of 325 mesh white hydrated alumina silicate, or equivalent) is blown into the enclosure at minimum velocity of 27 m/sec (60 mph) for 1 hr. The foam collectors are then removed and visually inspected for dust accumulation.
Wind-driven rain	IEC 60068-2-18 Test Ra, Method 1, using a four-quadrant spray chamber simulating 40-mph, 70-in/hr rain for a minimum of 4 hrs.	70-mph wind and 5.8-in/hr rain per GR-487-CORE

10

Other tests include UV weathering effects from sun exposure:

- UV-A exposure with fluorescent lamps per IEC 60068-2-5, procedure B at 55°C for a minimum 240 hours
- Full spectrum UV-A/B exposure with xenon arc lamps per ASTM G155
- Other multi-year outdoor weathering tests in urban environments

Lightning protection:

- Test per IEC 61000-4-5, 1.2/50µs Voltage 8/20µs Current Combination Waveform, 10 repetitions @ ±6kV, ±3kA.

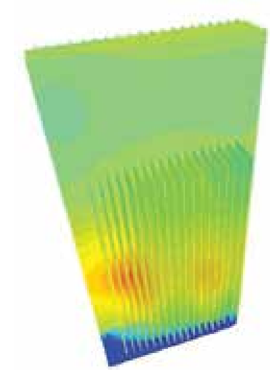
Some examples of testing and analysis in action are shown below (figures 10.7 through 10.10).

Group 1 | *Group 1, 1000 hours of corrosion* | *Group 2* | *Group 2, 1000 hours of corrosion*

10.7: Weathering and corrosion test of silver-plated steel products

10.8: UV and weathering test of base station antenna assemblies

10.9: Outdoor wireless cabinet thermal testing



10.10: Remote radio head subassembly thermal simulation

Robustness and life testing

Accelerated life testing (ALT)

ALT is performed to demonstrate the long-term reliability of a product. During ALT, a sample of units is subjected to more severe thermal conditions than would normally be experienced in the field. This is implemented with a greater temperature excursion and an increased frequency of thermal cycles. Though product variable, a typical ALT includes high temperature dwells and thermal cycling to stress the unit's electrical components as well as their mechanical attachments. The duration of the testing is again product variable, but typical testing can last 60-100 days to evaluate the product's long-term reliability.

Highly accelerated life testing (HALT)

HALT reveals latent defects in design components and manufacturing that would not otherwise be found by conventional test methods. HALT stresses the products to failure in order to assess design robustness and marginality. Our regime includes:

- Step temperature stress
- Voltage stress
- Thermal dwell stress
- Rapid thermal cycling stress
- Random vibration stress
- Combined thermal cycling-vibration stress
- Other stress tests that may be product applicable

Recent developments in reliability

While it's easy to establish areas of attack when it comes to improving reliability turning those insights into real-life design advances requires a great deal of experimentation and testing. For every theoretical opportunity, there is a practical obstacle, but **CommScope** is dedicated to leading the charge for improved reliability on every available front.

Thermal design

In the arena of thermal design, **CommScope** is always working to develop new designs and alternative materials to make heat sinks that more effectively transfer heat from components to the air. This approach means less reliance on costly and failure-prone cooling fans. As mentioned earlier, every 10°C reduction in operating temperature doubles reliability.

Internal redundancy

CommScope is focused on load-sharing redundancy to improve system availability. While not every single subsystem can be built to ideal fault tolerances, we're making every effort to cover as many subsystems as possible.

Field data analysis

CommScope continuously monitors field returns and performs root-cause analyses on those returns. These analyses inform our design and manufacturing processes, so we can prevent potential problems at the source rather than on the tower—and field results prove that the process works, showing continuous improvement over time. We're building a whole new layer of reliability right into each product.

Industry forums

In 2008, the International Wireless Packaging Consortium convened the Tower Top Reliability Working Group to address carrier concerns over the reliability of tower-mounted equipment.

The best minds from carrier companies, equipment suppliers and other industry experts split into subgroups in order to draft a comprehensive best practices document. Results will be published at future IWPC proceedings and early results suggest that the study will become an ongoing fixture in the development of industry standards.

CommScope is proud to share our expertise, as we are well-represented in several key subgroups and lead the team dealing with reliability prediction.

Ensuring a reliable network

In wireless communications, every design choice involves a tradeoff. In exchange for more efficient use of power and space in cell site deployments, there exists a greater risk of component failure. Such failures are a part of life, but, they have to be part of the plan.

Predicting and measuring reliability can be a complex process with many competing aspects. Determining the reliability of a component, a subsystem or an entire cell site depends heavily on what matters most: maintenance time, upkeep costs, fault tolerance and a host of other considerations. There are ways to improve reliability, but the tradeoff in cost may not always be worth it.

In modern communications, there are no "one-size-fits-all solutions." Every step to improve reliability represents a careful balancing act between performance expectations, installation, and maintenance budgets and risk tolerance. **CommScope** helps make those decisions easier with the technology and insight that lets you choose the right solution from the best available options.

Chapter 10 summary

Reliability in wireless systems

- More tower-mounted equipment improves efficiency but poses challenges to reliability and maintenance.
- Reliability over life span defined by bathtub curve

Reliability stress factors

- Temperature extremes
- Environmental stress
- Heat and heat dissipation

Measurements of reliability

- Failure rate
- MTBF
- MTTR
- Availability
- Unavailability
- Downtime

Reliability prediction tools

- FMEA
- RBD
- Markov Model

Testing regimens

- Design verifications testing (DVT)
- Accelerated life testing (ALT)
- Highly accelerated life testing (HALT)

Reliability improvement opportunities

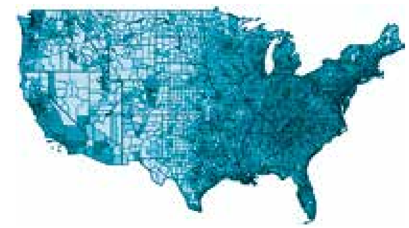
- Product simplification
- Redundant hardware
- Better heat dissipation
- Installation best practices
- Improved prediction tools
- Field data analysis and integration of findings into production processes
- Industry forum leadership

Chapter 11

Covering all the bases:
Distributed antenna systems

A population map of the United States illustrates what you already know: people are not evenly distributed across the country, or even across a particular state (figure 11.1).

Since cell network service is driven in large part by the population it serves, it makes sense that coverage must be denser in those places where population is denser. While this map shows how population density changes from state to state and from county to county, it doesn't show how density changes from one neighborhood to another, or even from one building to another. These localized differences matter in cell network planning, defining cell size, shape and power requirements. A key part of that plan is the *distributed antenna system (DAS)*, which serves geographical areas and buildings with the highest demands.



11.1: A map of the United States showing relative population density

Distributed antenna system (DAS)
A network of nodes serving a specific place or building. They connect through a central base station for backhaul out to the public network.

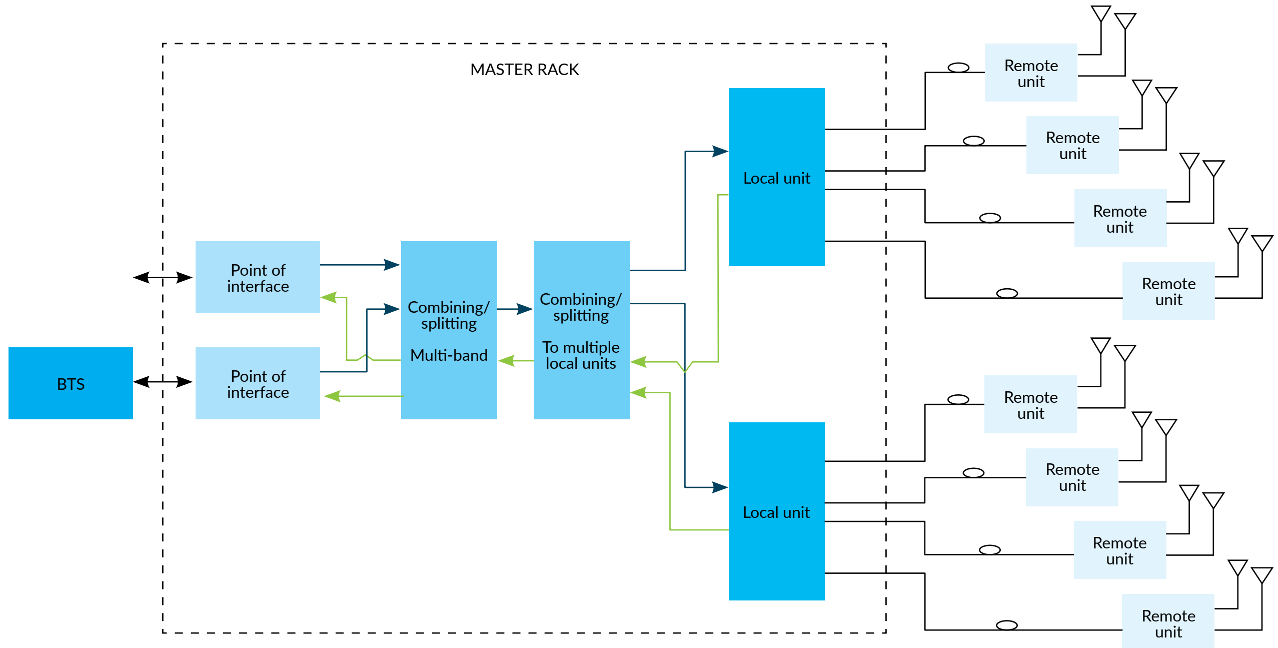
A DAS is a network of spatially separated antenna nodes—called microcells—arranged to support cell network service in a particular place, often a single building or a campus of buildings (figure 11.2).

11.2: An overview of a typical DAS deployment

These nodes are compact, so they can be placed almost anywhere. DAS nodes typically have smaller footprints than macrocells. You can see a diagram of DAS architecture in figure 11.3.

DAS systems can be used to support an amazing variety of different communication and data network services, from analog to cutting-edge LTE and WiMAX (table 11.4).

This flexibility, combined with their small size and ability to cover small, specific areas, makes DAS an ideal means to extend or improve cellular service into locations that lack adequate coverage. Sometimes this need is a result of problematic location or geography, and; other times by limited network capacity. In either event, a DAS system can be a direct connection to the public network for locations unserviceable by macrocells.



11.3: A summary of DAS-supported frequencies and network services

Frequency range	Service types
700 MHz	Analog, GSM, LTE
800 – 850 MHz	Analog, GSM, iDEN, CDMA
900 MHz	Analog, iDEN
1700 MHz	CDMA, W-CDMA, LTE
1900 MHz	Analog, CDMA, W-CDMA
2600 MHz	WiMAX

11.4: A summary of DAS-supported frequencies and network services

DAS can be deployed indoors, outdoors and even in places that are a combination of the two, such as:

Indoor

- High-rise apartment or condo buildings
- Large corporate offices
- Exhibition halls and shopping centers
- Hotels, hospitals and restaurants

In these installations, nodes are arranged to provide even coverage across each area or each floor. An example of an indoor DAS layout appears below (figure 11.5).

Outdoor

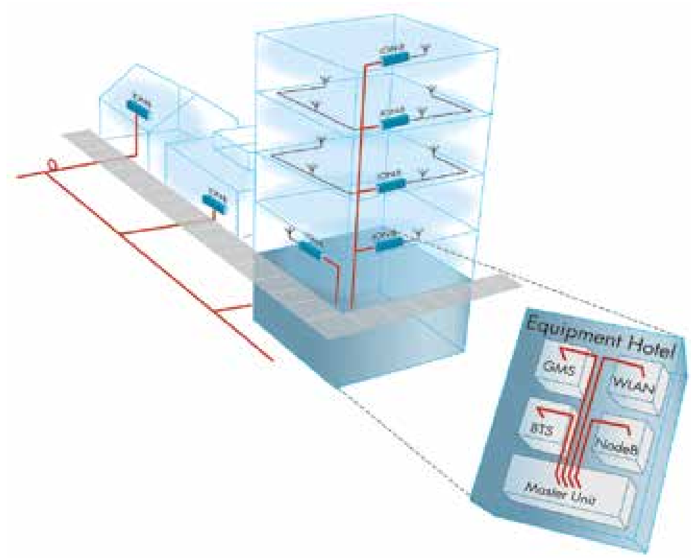
- Open metropolitan areas
- Railways

Outdoor deployments create service areas in the open, but the architecture remains basically the same as an indoor DAS (figure 11.6).

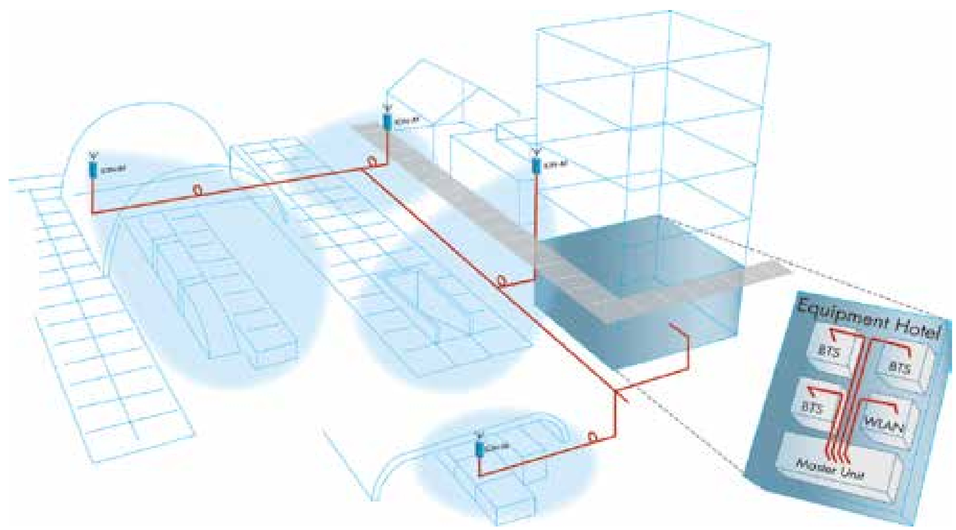
Combination

- Corporate campuses
- Industrial parks
- Airports
- Stadiums
- Subways, tunnels and trains

Combination DAS layouts include elements of both indoor and outdoor designs.



11.5: An indoor DAS layout for a building—remote nodes connect to the base station



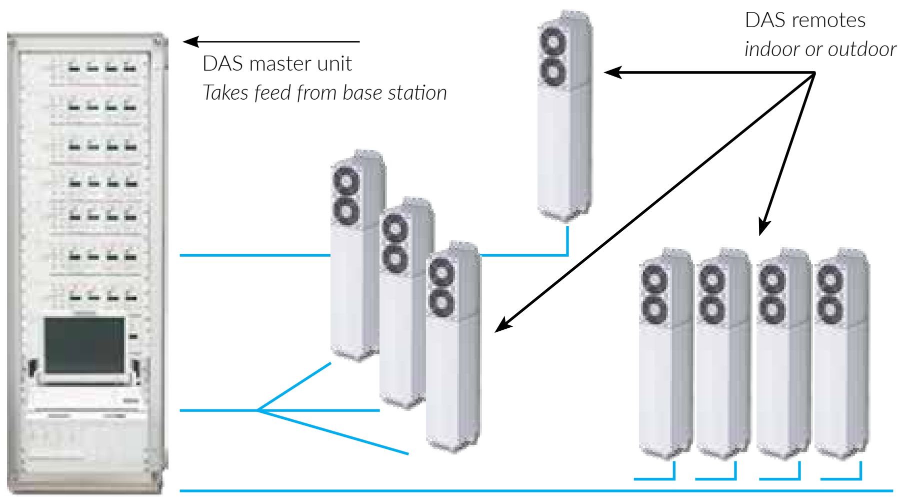
11.6: Outdoor DAS layout—nodes create service areas outside

DAS components

A DAS network layout is based on three core components:

1. **Master unit.** This is the DAS interface to the outside world, connected to a nearby macrocell base station that provides access to the larger network.
2. **DAS remotes.** These distributed devices receive traffic from the master unit via optical cable and relay RF transmission to and from the antenna via coaxial cable.
3. **DAS antennas.** These are the entry and exit points between the DAS and individual network users. They relay traffic to and from the remote.

Seen together, you'll notice that the entire system starts to resemble the topology of an ordinary computer Ethernet network, in which a central server connects to individual workstations as well as to any outside networks, such as the Internet (figure 11.7).



11.7: Typical DAS components—the antennas connect via coax to remotes

DAS in practice

Perhaps the best way to understand how a DAS can bring enhanced network service to a specific area is to look at a few real-world examples.

Indoor DAS deployment: Rome Telecom Italia Mobile

A corporate office building provides all the networking challenges DAS was designed for. In general, these environments are characterized by:

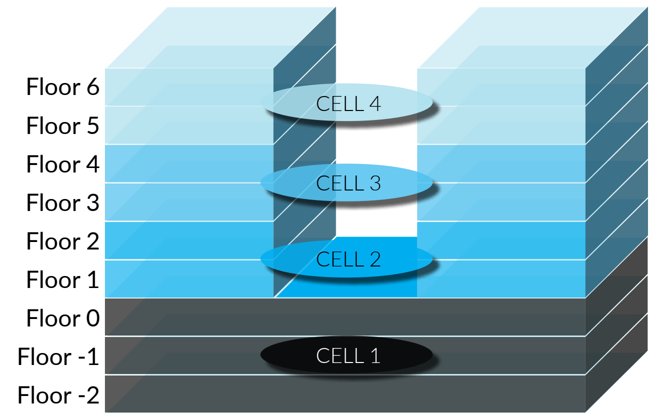
- **Large, dense populations of users.** The DAS must meet and maintain reliable service in high-traffic situations, whatever the circumstances.
- **Scaling needs for service.** The DAS must be able to offer seamless coverage from one node to the next and scale itself to meet the changing capacity requirements of users as they move through the building.
- **Ever-evolving service needs.** As technology changes and future-readying becomes a necessity, the DAS must be able to add or remove services without disrupting access or degrading performance, including those shown above in table 11.4.

A good example of a DAS that meets all these needs is the ION-B system offered by **CommScope**. The ION-B series can manage multiple technologies over several bands simultaneously. Depending on the situation, a designer may choose single-band, dual-band or triple-band versions with wireless LAN (WLAN) on an auxiliary channel.

Rome Telecom Italiaia Mobile (TIM) needed a reliable DAS solution that would link users at their headquarters.

CommScope delivered a DAS network that met all these requirements, with a slim public profile.

The layout of the DAS reveals the structure of data flow throughout the two buildings, including in hard-to-serve places like the two underground parking levels and stairwells (figure 11.8). The system was installed and optimized in just four weeks and featured four IP-based base transceiver stations to support the high traffic requirements between the DAS and the outside network.



11.8: Layout of the TIM HQ system, connecting two buildings through a single DAS

Combination indoor/outdoor deployment:
Dallas/Fort Worth International Airport

Airports are high-traffic areas in more ways than one. In the dynamic world of air travel, expansion and evolution are inevitable. DAS serving an airport's personnel and its travelers must be able to expand and evolve as well. Like most indoor/outdoor installations, an airport DAS must offer:

- **Flexible service support.** With so many different technologies on the airwaves, an indoor/outdoor DAS must support the standards of today and tomorrow.
- **Broader coverage areas.** By definition, indoor/outdoor deployments tend to cover wider spaces and more diverse terrain. Expanding the DAS range cannot come at the cost of reliability or speed.
- **Steeper demands for on-the-fly scalability.** Wider coverage areas have greater potential traffic needs. For efficient operation, the DAS must be able to dynamically allocate capacity where and when it is needed.

Again, the ION-B® series from **CommScope** proved an effective solution for these challenges, as well as other specific circumstances related to our DAS installation at the Dallas/Fort Worth International Airport.

Dallas/Fort Worth International Airport:

- A busy cargo and passenger hub for multiple carriers
- 5 large terminals dispersed over an area of 18,000 acres
- More than 28,000 parking spaces in ramps and lots
- Over 56 million passengers and 630,000 flights annually

The DAS solution would need to:

- Cover vast spaces between terminals and parking areas
- Include capacity for public safety traffic
- Scale with airport growth
- Allow flexible leasing by airport management to multiple participating partners
- Be designed and installed quickly with minimal environmental impact
- Not interfere with other RF traffic in the area

The CommScope solution:

- Phase 1
  - 128 remote units
  - 218 antennas
  - 150,000 meters of fiber-optic cable
  - 30,000 meters of coaxial cable
- Phase 2
  - 58 remote units
  - 182 antennas
  - 5,500 meters of fiber-optic cable
  - 10,000 meters of coaxial cable
  - 10,000 meters of composite cable

Andrew integrated management and operating system (A.I.M.O.S.)
The network management solution for all **CommScope** distributed antenna systems. Part of our Andrew Solutions portfolio, it performs configuration fault and inventory via SNMP for alarm forwarding.

CommScope provided the right solution in a ION-B system with all the power and flexibility needed to meet the airport's present and anticipated future challenges.

To address the long distances between components, the optical links between remotes and master units were rated for signal integrity up to 20 kilometers. This meant remote units could be placed literally anywhere on the property and still communicate effectively with the master unit.

The ION-B system is also transparent over its full operating bandwidth (from 800 MHz to 2500 MHz) so each licensed user within the airport's hierarchy could count on top performance without interfering with other RF traffic in the area.

Cellular and other wireless signals from passengers, personnel and safety officials are distributed down hallways, into alcoves and through corridors. Intelligent network management also permits priority service for emergency responders.

To control maintenance and monitoring costs, the ION-B also allows remote, Web-based supervision by such common protocols as TCP/IP, SNMPv2, FTP or Telnet with its integrated *Andrew integrated management and operating system (A.I.M.O.S.)*. To date, four wireless providers have leased access to the network.

Combination indoor/outdoor deployment: Allianz Arena Munich

While the installation at Dallas-Ft. Worth International Airport (DFW) presented unique challenges in regard to area of coverage, stadiums and other indoor/outdoor applications require special attention to matters of variable capacity. While meeting all the requirements of the DFW example, a stadium installation must also deal with the additional task of assuring QoS in hard-to-serve indoor spaces as well as open-air spaces above. This is not only for the fans in the seats, but the enormous media presence required to broadcast the biggest events to a global audience.

For the Allianz Arena in Munich, **CommScope** deployed the ION-M series precisely because it could address these specific requirements.

Because the **CommScope** ION-M series can transmit on several bands simultaneously – with no restriction on the number of carriers – it was the natural choice for this application.

The combination of high-powered remotes and a flexible master unit allowed easy customization to penetrate even the hardest-to-serve locations. To scale along with the significance of the events taking place, ION-M also supports multiple configurations, like point-to-point, star and daisy-chain.

If fiber-optic cable access is limited, both coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) can be used to establish multi-sectored sites with a single fiber connection. With all the maintenance and monitoring capabilities of A.I.M.O.S., the system offers cost-effective upkeep.

To date, four operators have signed contracts to use the system, which has proven equal to the task of keeping fans and the media connected – even for the most important tournaments.

Allianz Area:
- Home field for two German soccer teams
- Sitting and standing capacity of nearly 70,000 fans
- Hosted the globally broadcast FIFA World Cup in 2006
- Will play host to UEFA Championship Finals in 2012

The DAS solution would need to:
- Accommodate a full house of users without overloading the network
- Support multiple services such as GSM900, GSM 1800 and UMTS

The CommScope solution:
- 28 remote units
- 350 antennas
- 150 meters of radiating cable

Coarse/Dense Wavelength Division Multiplexing (CWDM/ DWDM)
Methods of duplexing signals in an optical cable by using different colors of laser light for increased capacity.

Swiss high-speed rail project:

- Route between Heitersberg and Däniken covers 20 km
- High-speed trains may travel up to 300 km/hr

The DAS solution would need to:

- Accommodate seamless handoffs between cells
- Manage calls through multiple operators
- Support GSM900, GSM1800 and UMTS services
- Cost significantly less than a macrocell solution

The CommScope solution:

- 24 remote units
- 48 antennas

Outdoor DAS deployment:

Swiss Rail Corridor from Heitersberg to Däniken

Full outdoor deployments place unique demands on the design of a DAS. It becomes even more challenging when the average network user is passing through your service area at more than 300 kilometers an hour, as they do on European bullet trains. For passengers to connect while they ride the rails, they need a DAS that offers:

- **Seamless coverage and capacity.** Handoffs between cells is tricky when the user is moving through at bullet train speeds, yet dropped calls are not an option.
- **Closed coverage.** Clean connections to the macro network keep the signal clear no matter what kind of interference sources the train is passing at the moment.
- **Remote administration and maintenance.** When the DAS is miles long, remote management capabilities are critical.
- **Multiple carrier support.** To keep development costs reasonable, the DAS must offer shared infrastructure to support multiple carriers simultaneously.

When the Swiss rail lines requested that **CommScope** build a DAS that would keep their passengers as connected as they were comfortable, even at the highest speeds, these stringent criteria put us to the test.

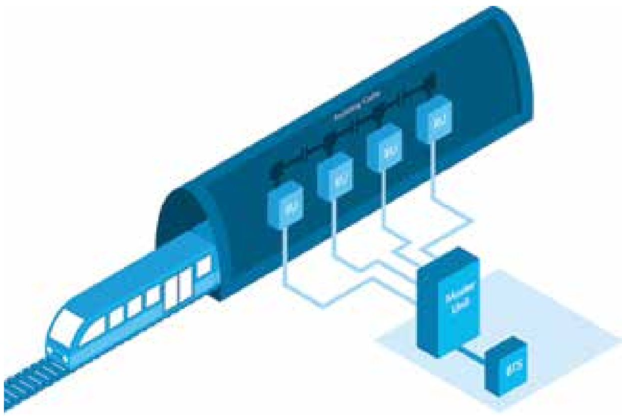
The ION-M system proved the best solution. By creating several radiation points along the length of the track, the cells comprising the DAS elongate and stretch in just the right direction to perform reliable handoffs, even at top speed. The coverage is dedicated and localized, keeping outside interference at bay and assuring enough capacity for the most crowded passenger trains.

All master unit equipment is concentrated in the BTS interface located in the middle of the track, while remote units are spaced along the length of the track. By elongating the cells, **CommScope** was able to achieve distances between remotes of up to 2 km, and with the integrated A.I.M.O.S. capability, system monitoring and adjustment can be performed remotely.

Outdoor DAS deployment:
The Moscow Metro underground

When the same technology is applied to subterranean settings with limited access, distances between remotes and master units become even more important. Both the ION-B and ION-M series guarantee signal quality for distances up to 3 km. By applying the optical link option, theoretical distances of up to 20 km are possible, helping future-ready the system against growing capacity needs.

As users and their associated network traffic move from one part of the DAS to another, the remotes must be powerful enough to manage dynamic changes in capacity while remaining small enough for safe installation in tight spaces found underground. In the case of the Moscow Underground, we find that reliable communications are much more than a matter of passenger convenience. They can make the difference in the event of an emergency situation as well.



11.9: The ION-M deployment in the Moscow Metro underground

The Russian government ordered a DAS system that would provide seamless communication through the vast underground network, both for passenger convenience and for emergency responders, due to the threat of terrorist attacks. This capability was also needed for more commonplace emergencies such as fires, accidents and other injuries. As a government directive, installation time was of the essence.

CommScope designed and installed a dedicated ION-M DAS using remote units that could be installed without damage to the legendary décor of the Metro's elegant stations, which are often called "underground palaces" (figure 11.9).

Indoors, outdoors or both—the right solution makes the connection work

All these examples bring dedicated cellular services to locations that were not otherwise accessible, or at least not reliably accessible. A DAS network can achieve this primary objective by several methods, but the result is always the same: better, more reliable coverage, indoors and out.

Moscow Metro underground:

- 12 lines with 182 stations and a total rail length of 301 km
- 11 million riders daily
- A historically high-profile target for terror attacks

The DAS solution would need to:

- Increase security efficiency
- Provide highest reliability
- Offer fast access for emergency responders
- Present little or no visibility
- Be delivered on a very aggressive schedule

The CommScope solution:

- 260 remote units
- 10 master units
- 400 km of radiating cable

11

Capacity on demand, wherever it's needed

If the world's population were evenly distributed, designing the perfect cellular network would be as simple as drawing circles on a map. When the Swiss rail lines requested that CommScope build a DAS that would keep their passengers as connected as they were comfortable, even at the highest speeds, these stringent criteria put us to the test. Since the real world is full of high-density and low-density population centers, as well as variations in geography, government oversight and terrain, we need to adjust our methods. It's the only way people can connect…no matter where they are.

As more and more places are connected to accommodate our on-demand world, companies like **CommScope** continue to innovate new ways to improve service while reducing visibility, bringing access without eyesores.

Distributed antenna systems help service operators reach their customers in crowded buildings, deep underground and even as they cross the countryside at hundreds of miles an hour. They can connect a stadium of die-hard fans to their loved ones at home and let the whole world watch what's happening on the field below in real time—one of the many benefits of putting the right communication infrastructure to work.

Chapter 11 summary

Distributed antenna systems (DAS)

- Microcell solutions
- Compact, flexible and scalable
- Support for multiple services

Best circumstances for DAS

- Poor existing coverage
- Variable capacity requirements
- Exceptionally dense traffic areas
- No cost-effective macrocell solution

Indoor deployments

- Ideal for office buildings, shopping centers, apartments, expo halls, hotels and hospitals

Outdoor deployments

- Ideal for railways, metro areas and other outdoor spaces

Combo in/outdoor deployment

- Ideal for office campuses, airports, stadiums, subways and moving trains

DAS components

- Master units
- DAS remotes
- DAS antennas

Chapter 12

Going to ground:
Lightning protection

Even in the 21st century, the source of atmospheric lightning is the subject of scientific debate. Different theories assign different mechanisms to the creation of lightning: wind and friction, ice formation inside clouds—even the accumulation of charged particles from solar winds.

Far better understood is the behavior and power of lightning. We've all been cautioned not to stand out in the open during a lightning storm—and for good reason. A lightning bolt can reach temperatures of 54,000° Fahrenheit, five times the temperature of the sun's surface and hot enough to fuse loose sand into hard glass in an instant. Superheated air around the bolt expands violently as it passes, creating the familiar deep rumble of thunder.

Like any electrical discharge, lightning always seeks the path of least resistance to the ground. Often, this is through the tallest or most electrically conductive object available, which is why you don't want to stand in an open field during a storm. The human body presents the shortest path into the earth, boosting conductivity by shaving five or six feet off the distance a bolt must travel through the air.

Lightning by the numbers

In the 30 microseconds it exists, an average lightning bolt (at its peak discharge level) can carry:

- 30,000 amperes of current
- 1 trillion watts of electricity
- 500 megajoules of energy

But how do we deal with sensitive electronics that can't take shelter from the storm? One look at a cell antenna tower will tell you that, by virtue of its metallic composition as well as its height, it's a prime target for lightning strikes. A number of components are particularly attractive to lightning, including:

- Antennas and their support structures
- Coaxial lines and waveguides
- Steel buildings, cabinets and other equipment housing
- Connected communication and power lines

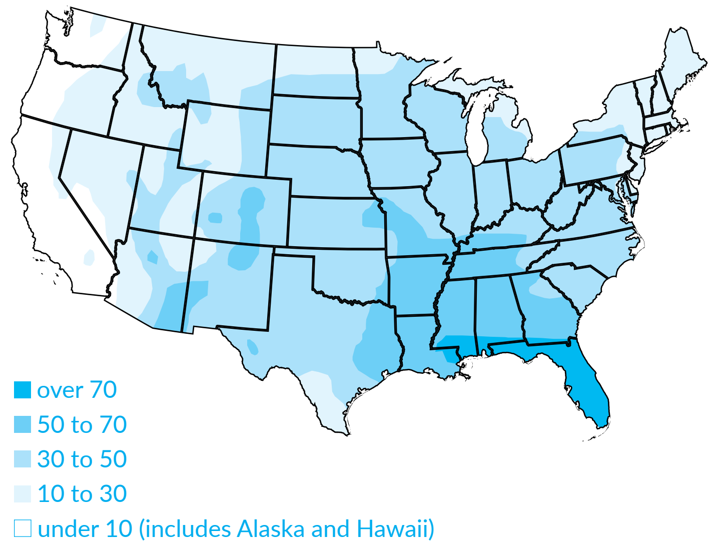
This exposure opens up the installation to expensive damage, maintenance and downtime, so it's vitally important that we take protective measures to minimize the risk of lightning damage.

Understanding the risks

Unfortunately for planners, most of the risk factors for lightning strikes are the same characteristics that make for a good cell site: open land and high elevation. Since there is little that can be done about location, lightning mitigation efforts must be directed elsewhere. Let's look first at the two types of meteorological events that present the greatest risks:

- Convection storms are caused by the heating of air near the ground and its interaction with cooler air above. These create the localized, short-lived storms we see most often in the summer months.
- Frontal storms are created by warm and cool fronts meeting. These storms can extend hundreds of miles and regenerate their strength over and over again, allowing them to persist for days and affect enormous areas. Frontal storms present the greater lightning risk.

The overall pattern of these storm types can be anticipated by season and location. Historical trends are accurate predictors of future activity. While government statistics don't include specific numbers regarding the number or severity of lightning strikes, they do provide overall counts of thunderstorm days in a given area (figure 12.1).



12.1: A meteorological map showing the annual number of thunderstorm days

The nature of lightning

Lightning occurs in two common forms:

> **Cloud-to-cloud lightning** discharges itself by equalizing its charge with another cloud, remaining high above the ground in the process.
>
> **Cloud-to-ground** lightning seeks discharge through the earth. This is the kind that creates problems for objects on the ground, including cell sites.

In both cases, the lightning occurs when a difference in electrical charge—the *electrical potential*—exists. When this difference grows to a magnitude that overcomes the natural insulating properties of the air, the electrical difference seeks equilibrium by discharging itself along the path of least electrical resistance. For cloud-to-ground lightning, the less distance traveled in the air, the easier it is to discharge. That's why it seeks a more conductive object on the ground as its preferred path.

In most cases, this discharge represents a negative charge seeking a positive charge and may represent an electrical potential of as much as 100 million volts.

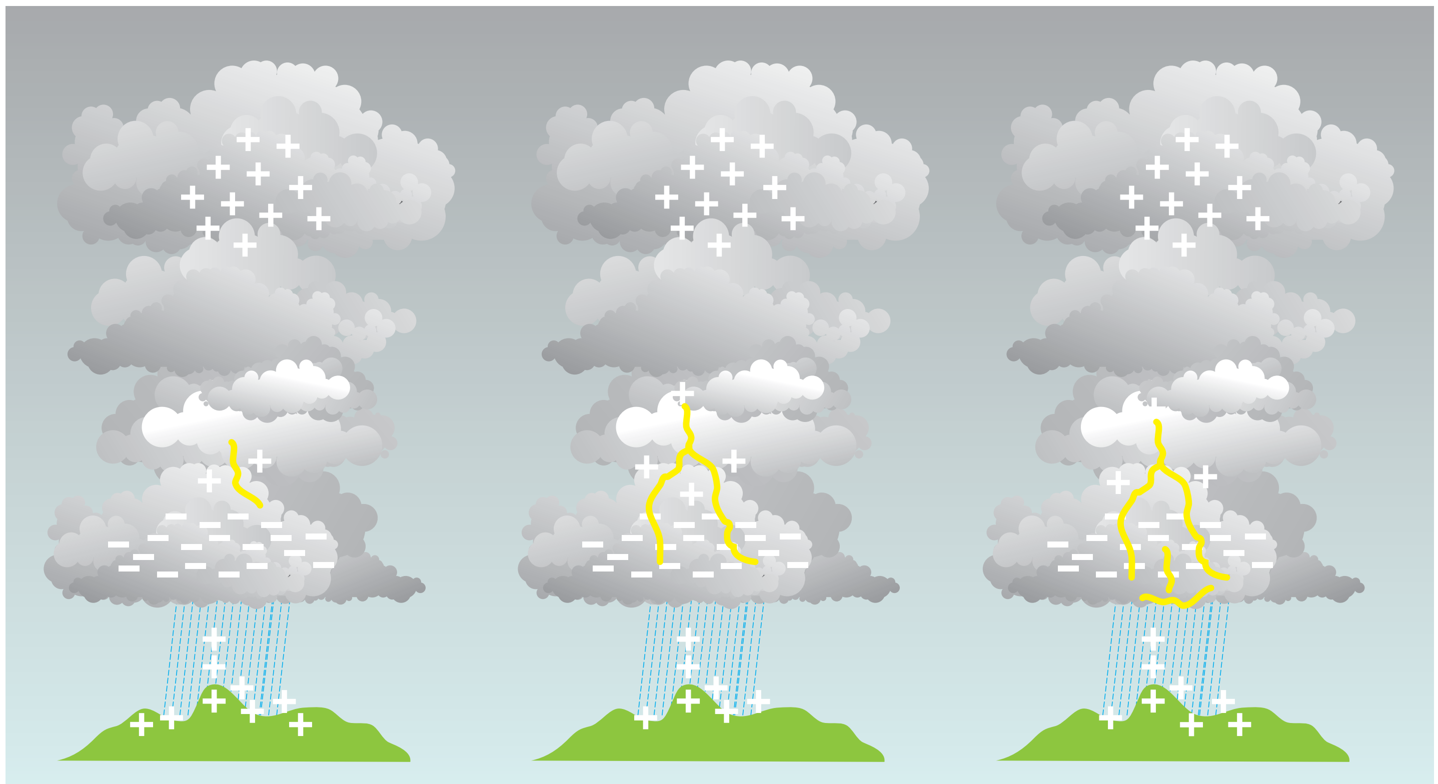
Electrical potential
Measured in volts, this is the difference in electrical charge between two points in space. The greater the difference, the higher the potential, and therefore, the greater the voltage.

Coaxial cable
A type of cable featuring an inner conductive core, an outer conductive layer and a dielectric, or insulating, space between them. Coaxial cable connects antennas to their base stations.

The birth of a bolt

As we can see in the three-step illustration below, cloud-to-ground lightning begins as a faint or invisible “pilot leader” high in the cloud. As it progresses downward, it establishes the first phase of the strike path. This pilot leader is followed by the “step leader,” a surge in current following the new path. The step leader jumps in roughly 100-foot increments, or steps, until it approaches the positively charged point on the ground.

At this point, something incredible happens: a secondary discharge extends upwards from the ground, meeting the bolt in midair and completing the circuit. It happens so fast that the human eye only sees the bolt descending from the sky, not the one reaching up from the ground (figure 12.2).



12.2: The origination and path of a cloud-to-ground strike

The intense light of a lightning bolt is created by molecules of air energized by the current passing through them. The shape of the visible lightning can help you identify its type:

Streak lightning is the most commonly seen type, characterized by a single line running from cloud to cloud or cloud to ground.

Forked lightning reveals the full conductive channel as smaller tributaries branching off the main line.

Sheet lightning is a shapeless, wide-area illumination commonly seen in cloud-to-cloud discharges.

Ribbon lightning is a streak that seems to repeat itself in a parallel path. This is due to high winds moving the air in the midst of the strike.

Beaded lightning, also called chain lightning, appears to break up into separate branches and persist longer than the main strike.

Heat lightning is not truly a lightning type, but the red-tinted appearance of other lightning types visible on a distant horizon. The coloration is due to atmospheric reflections and light scattering between the lightning and the observer.

Dealing with lightning

Now that we know a little about the challenges we face, let's look at some of the ways we can guard against the damaging effects of lightning.

The science of grounding

All electrical facilities are inherently connected to the ground, either by design or by circumstance. The earth itself represents the common electrical potential, or voltage, that other electrical sources naturally seek for equilibrium. By improving the way these discharges reach the earth, we can control the path and divert its damaging power away from equipment and structures that would otherwise be harmed.

When you imagine an electrical *grounding* system, you may have an image of a simple lightning rod with a wired connection to the ground. In the case of cell site installations, a grounding system is much more complex and serves purposes other than simply diverting lightning strikes; it also minimizes the chance of shock from the equipment itself, reduces noisy voltages that interfere with signals and protects sensitive electronics from damaging overvoltage conditions from all sources.

Grounding
Measures taken to control and facilitate the path of an electrical discharge from its source to the ground, avoiding potential damage to sensitive equipment along the way.

Grounding limits

As important as effective grounding is, it's often not enough by itself. Any path you install to ground a discharge has a certain physical limit to the voltage it can handle. Even the most substantial methods, like water pipes and specially designed grounding rods, are restricted as to how much voltage they can pass to the ground. To address these limits, it's wise to design in multiple paths so the grounding system can dissipate the most voltage possible.

Protecting the tower

The antenna tower presents the most obvious electrical target, as well as the best opportunity to protect the rest of the installation. That's because drawing lightning to the tower for safe discharge also gains us valuable insurance for the harder-to-protect components down on the ground and those connected by transmission lines.

By its very nature, a tall metallic tower can conduct lightning current into the ground. The danger arises when the voltage exceeds the structure's ability to dissipate it and electrical arcing occurs. This current can damage microwave antennas and, in particularly powerful strikes, fuse the dipole elements of two-way radio antennas.

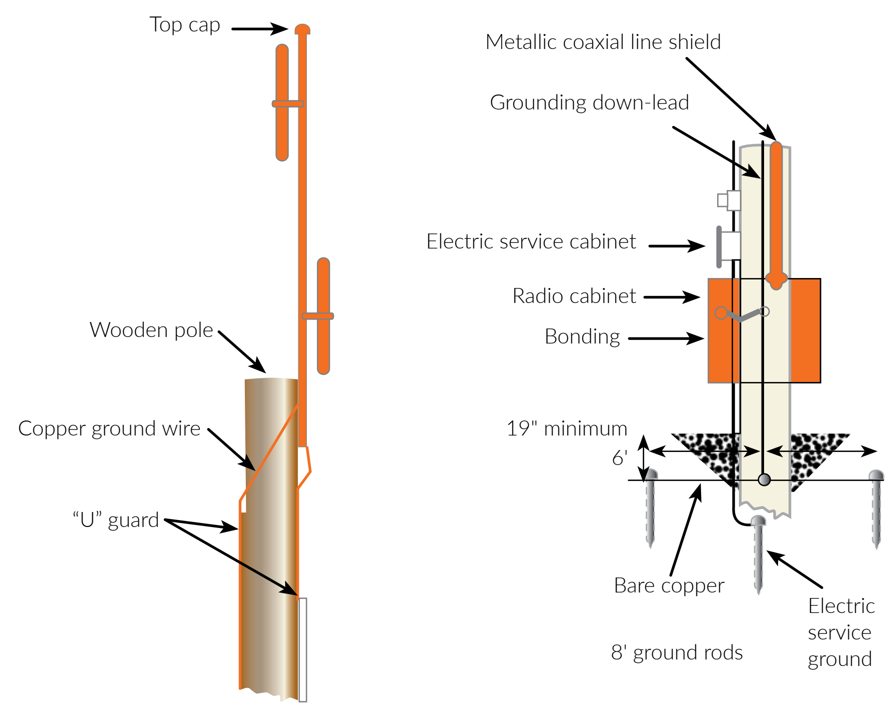
To protect these and other components mounted on metallic towers, lightning rods should be affixed directly to the tower above the components to assure safe interception of the strike. It's also important to ensure that the tower's base, footings and any guy wires are also properly grounded.

Additional protective measures include insulating gaps built into the design and devices called shorting stubs that can be added to allow a short circuit at lightning's natural frequencies. We'll dig deeper into these measures on the following pages.

Wooden tower structures

In wooden structures, conductive paths must be added to give strikes a direct route to the ground. If wooden support poles provide a nonconductive obstacle from a metal tower, additional lightning rods should be affixed atop these poles to prevent them from splitting under the force of a strike and potentially collapsing the tower they support.

Rods for this kind of application are typically #6 AWG bare copper stapled to the pole on the side opposite the antenna's transmission line. This ground line should be connected to all equipment on top of the pole as well as any lines leading away to a connected shed or cabinet (figure 12.3).



12.3: Grounding details for a wooden pole-mounted antenna

Two-way radio antennas

Conventional coaxial dipole antennas are often fitted with a serrated washer that forms a physical gap between the dipole whip and its support. Should lightning strike this point, the gaps in the serrated washer force the current to arc across the open space, creating a short circuit and dissipating the discharge.

Another protective measure is the insertion of a *quarter-wave shorting stub* in the coaxial transmission line at the base of the antenna. They're called quarter-wave shorting stubs because their place in the circuit does not impact normal operating frequencies of the site, and their length (a quarter of one wavelength), will cause an immediate short circuit for electrical frequencies associated with lightning. In this, they act as a sort of electrical "release valve" that will only divert a certain kind of dangerous current away from the system.

Other types of antennas tend to be self-protecting, such as folded dipoles, ground plane and Yagi antennas (chapter three for more information on different antenna configurations). These types are generally constructed of materials capable of handling most strikes, and their transmission lines are adequately shielded to direct any lightning current to the ground by other, easier paths.

Microwave antennas

Common types of microwave antennas, such as the paraboloid (dish-shaped) and horn reflector varieties are generally rugged enough to sustain normal lightning strikes without damage. However, the warning lights visible atop these installations are not so durable. To protect these regulatory-mandated devices, lightning rods are used to divert lightning discharges away from their more delicate wiring.

These protective systems may seem like a lot of expense to protect what are essentially blinking red lights, but the labor involved in replacing them after a lightning storm quickly becomes a costly maintenance situation.

Two-way radio antenna support structures

The buried end of a ground line can take several forms. Ideally, you would want the buried end to extend deep into the earth, providing a more reliable interface for dissipating the voltage. In some locations, such as rocky mountaintops, these depths aren't available. In these cases, the support structure can be protected by laying in multiple ground lines in a radial pattern to achieve horizontally what a single deep line would achieve vertically.

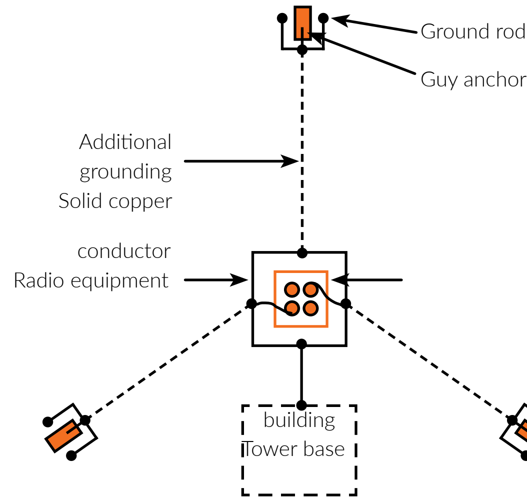
Quarter-wave shorting stub
A device inserted into the connection between transmission line and antenna that does not affect normal frequencies, but will immediately short and dissipate energy when lightning frequencies cross.

For antenna structures installed atop buildings—as is more frequently the case these days—all equipment, transmission lines and other conductive objects within a six-foot radius of the base should be commonly connected. The entire array should attach to a separate conductor with a minimum of two conductor systems integrated into the building itself. These conductors may be water pipes, steel framing or other electrically sturdy materials having direct contact with the ground below.

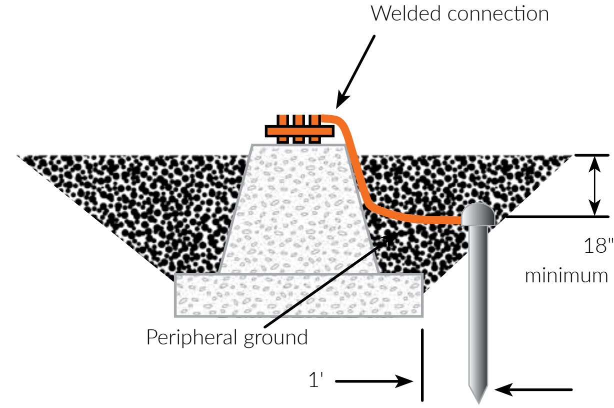
For those antenna structures mounted on metallic towers, grounding is a much simpler matter, since the tower structure itself provides a clear path to ground in the event of a lightning strike. Of course, this all depends on properly grounded base supports. Four methods of assuring this effect are shown to the right (figures 12.4 through 12.7).

For ground lines terminating through concrete bases and guy wire anchors, good conductive continuity inside the concrete itself should be virtually immune to any negative effects from lightning strikes. This is true for towers built on the ground as well as structures installed on top of buildings.

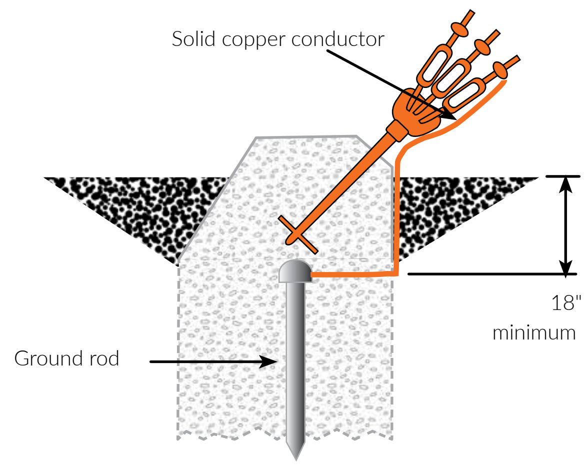
However, inadequate welds within the concrete may lead to electrical discontinuity, which can cause electrical arcing within the support...with potentially explosive results. For maximum safety, a secondary ground line is highly recommended.



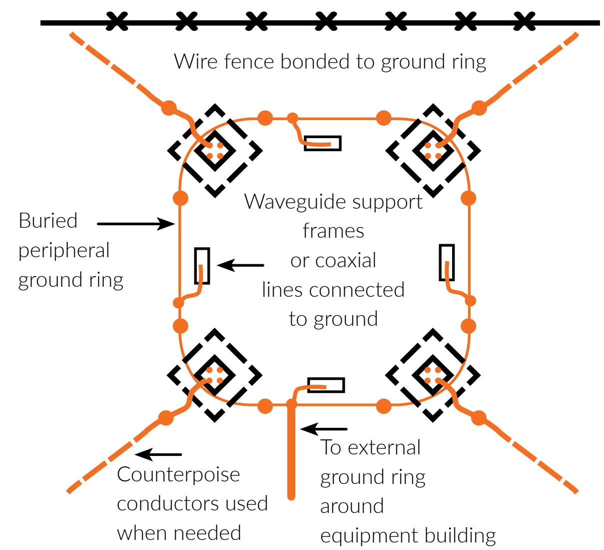
12.4: Support grounding installed in a tower pier



12.5: Support grounding achieved via guy wires



12.6: Support grounding installed in a tower's guy wire anchors



12.7: Support grounding for a freestanding tower structure

Coaxial transmission lines

Coaxial cables are subject to two potential hazards from surge currents reaching the outer conductor layer:

1. Damage to the insulating *dielectric layer* between the inner and outer conductors, which may destroy the cable and damage any equipment connected to it.
2. Mechanical crush forces that are associated with surge currents. While solid dielectric and larger cables (7/8" and up) are resistant to this effect, air dielectric and smaller-diameter cables have been known to be physically crushed by the magnetic effects of lightning-induced surges.

Providing a shunt path from the antenna to the ground line will usually prevent both kinds of damage. This danger highlights the rationale for securing the cables at such frequent intervals to prevent arcing between cable and tower.

Protecting the DC power system

As discussed in chapter 9, cell sites generally operate on DC power provided by the site's rectifiers. This energized part of the system presents an attractive target for lightning. The devices used to prevent overvoltage conditions are surge protectors. They work much like the consumer-grade version you may have installed in your home to protect sensitive electronics like computers or televisions.

Surge protector devices (SPDs) are in-line devices that feature a non-linear voltage-current characteristic which mitigates high voltages by increasing the associated current (figure 12.8).

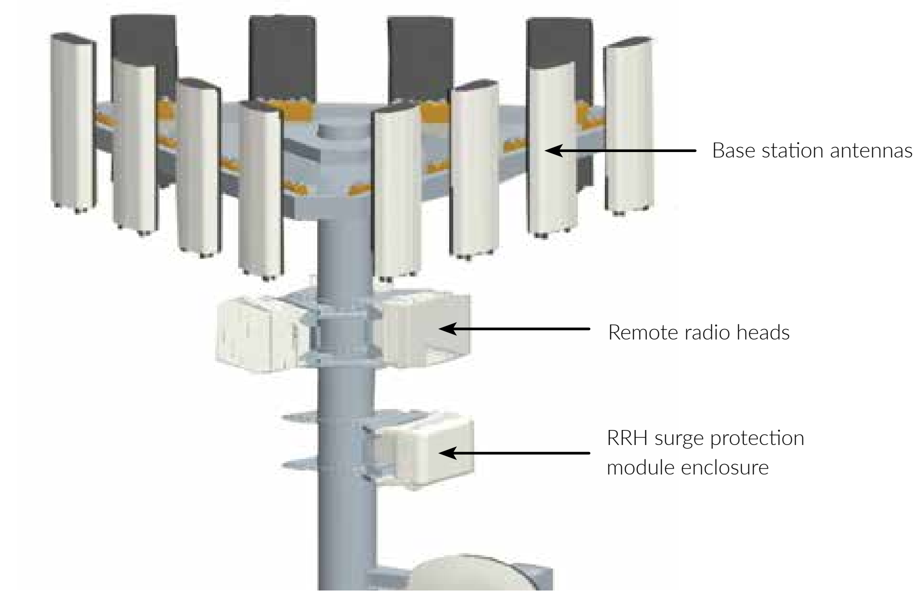
12.8: Typical surge protection devices (SPDs)

Dielectric layer
The insulated, tube-shaped layer separating a coaxial cable's inner and outer conductors. Dielectrics may be made of solid material, flexible foam or open air channels supported by nonconductive spacers. If the dielectric becomes damaged, the cable will short.

SPDs are used to safeguard all cell site components connected to the DC power system, but any devices connected to an external metallic conductor will require separate protection.

The most vulnerable components connected to the DC power system are remote radio heads (RRHs), which we discussed in chapter nine. Mounted as they are atop the cell site's tower and adjacent to the antenna, the RRH and its copper power cable are natural targets for lightning, much like the power distribution equipment at the tower's base. Insertion of SPDs as close as possible to these locations protects the RRH units from overvoltage damage (figures 12.9 and 12.10).

12.9: Vulnerable components at the top and base of a cell tower



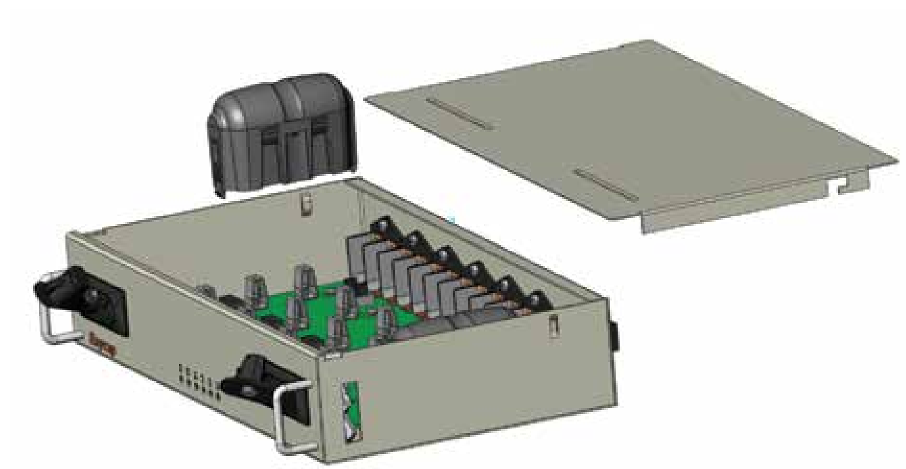
12.10: A surge protector mounted alongside the RRH

An SPD capable of withstanding not just one, but multiple lightning strikes must possess a robust resiliency to avoid costly maintenance and downtime for replacement. A detailed look at the inner layout of a sample RRH surge protection module appears below (figure 12.11).

Equipment at the base of the tower requires protection as well. Key components like the radio, the transmitter and backup battery systems, visible at the bottom of figure 12.9, are all vulnerable to damage from lightning-induced overvoltage. To prevent this, rack-mounted SPD units safeguard the power distribution system's connections between the RRH power cables and the rest of the equipment installed at the base (figures 12.12 and 12.13).

12.12: An SPD assembly mounted in a DC power and battery enclosure

12.11: Inside an RRH surge protector module, cover removed



12.13: The interior detail of an SPD unit designed to protect an RRH

Other forms of overvoltage protection: fuses and breakers

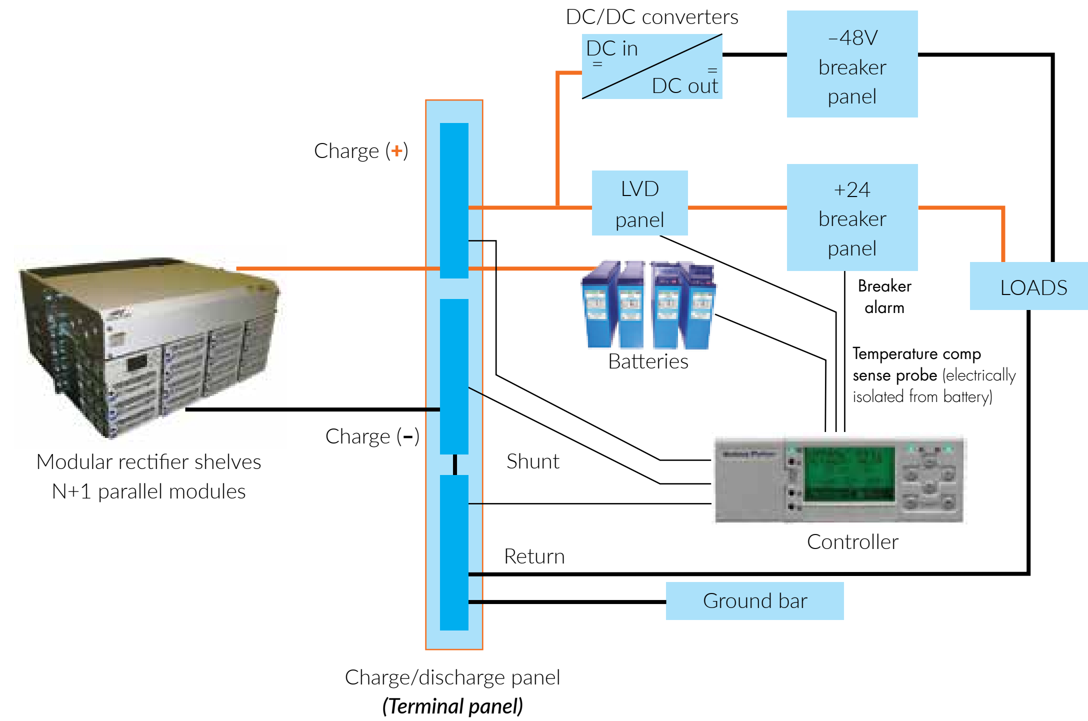
SPDs serve functions other than simply protecting components from lightning strike-induced overvoltage situations. As we learned in chapter 9, SPDs also offer protection in the form of fuses and circuit breakers that keep more common forms of overvoltage from damaging components and batteries.

In a cell site's DC power distribution system, as many as 80 circuit breakers may regulate DC power from the rectifier to all the connected loads, both in the enclosure and on the tower (figure 12.14).

Both fuses and circuit breakers perform the same basic function, which is to interrupt power to the load when levels grow unsafe. Examples of each are shown below (figure 12.15).

- Fuses incorporate conductors designed to melt under the stress of overcurrent conditions, breaking the circuit and protecting the load on the other end
- Circuit breakers incorporate short-delay curve or "fast-blow" fuses to break the circuit and protect the load

Because of the large number of circuit breakers required—often from 24 to 80 per cell site—wireless carriers have adopted modular distribution structures that accept a wide variety of circuit breaker sizes. You can learn more about these features in chapter 9.



12.14: Block diagram of +24V power and distribution system, typical of a cell site installation

Images and illustration courtesy of GE.

12.15: Commonly used telecom fuses and circuit breakers

Taming lightning by controlling the current

No matter how many times we witness it, the incredible power of a lightning bolt can instill fear and awe. When lightning strikes exposed cellular installations, only careful planning can divert its devastating power away from the sensitive components that keep modern networks operating.

With the right components, design and experience, a cell site can become virtually immune to the damaging effects of lightning as well as other electrically dangerous situations. **CommScope** supplies networks with the equipment and expertise required to harness lightning and direct it harmlessly away, keeping the world's key communications systems operating safely.

Chapter 12 summary

Lightning protection

- Lightning seeks a ground
- Providing safe paths around equipment protects cell sites

Lightning types

- Cloud-to-cloud
- Cloud-to-ground

Grounding an installation

- Metal towers can be self-grounding
- Wooden structures require paths
- Ground wire can travel deep or radiate horizontally

Tower and base station protection

- Remote radio heads (RRHs)
- Power distribution
- Radio, transmitter, battery backups

DC power system

- Surge protection devices
- Fuses and circuit breakers

Appendix A: Spectrum configurations around the world

Region	Countries	Frequency bands	Applicable technologies: GSM	CDMA	UMTS	LTE	WIMAX
Africa, Eurasia, South America	Argentina, Belarus, Czech Republic, Denmark, Georgia, Ireland, Latvia, Madagascar, Moldova, Norway, Peru, Portugal, Romania, Russia, Sweden, Tajikistan, Tanzania, Ukraine, Uzbekistan, Vietnam	450 MHz		✔			
Eurasia	Czech Republic, Hungary, Latvia, Mongolia, Romania, Russia	450 MHz				✔	
Africa, Eurasia	Cameroon, Kazakhstan, Moldova	450/800 MHz		✔			
Middle East	Iraq	450/800/1900 MHz				✔	
Asia, North America, South America	Canada, Kazakhstan, Peru, United States of America (USA)	700 MHz		✔			
Asia	Taiwan, Uzbekistan	700 MHz/2.6 GHz				✔	
North America	Canada, USA	AWS & 700 MHz				✔	
Europe	Germany	800 MHz				✔	
Africa, Asia, Caribbean, Central America, Middle East, Oceania, South America	Afghanistan, Angola, Australia, Bahamas, Bangladesh, Bermuda, Brazil, Cambodia, Cayman Islands, China, Colombia, Cote d'Ivoire, Ecuador, Fiji, Ghana, Guam, Hong Kong, India, Indonesia, Israel, Jamaica, Japan, Macau, Mongolia, Nepal, New Zealand, Nicaragua, Panama, Peru, South Africa, South Korea, Sudan, Taiwan, Thailand, Ukraine, Uzbekistan, Venezuela, Vietnam	800 MHz		✔			
Asia	Japan	800 MHz & 1.5 GHz				✔	
Europe	France, Germany, United Kingdom	800 MHz & 2.6 GHz				✔	
Europe	Germany	790 - 862 MHz				✔	
Caribbean, North America, Oceania, South America	Anguilla, Antigua and Barbuda, Argentina, Bolivia, Canada, Colombia, Ecuador, Guam, Honduras, Nicaragua, Northern Mariana Islands, Paraguay, Peru, Puerto Rico, USA, Virgin Islands (USA)	850 MHz/1900	✔				
North America, South America	Argentina, Canada, Colombia, El Salvador, Mexico, Nicaragua, Panama, Puerto Rico, Uruguay, Venezuela	850 MHz/1900			✔		
Asia, North America, Oceania, South America	Brazil, New Zealand, Pelephone, Philippines, Uruguay	850 MHz/2100 MHz			✔		
Caribbean, Central America, Europe, South America	Aruba, Belarus, British Virgin Islands, El Salvador, Honduras, Trinidad/Tobago, Ukraine, Venezuela	850 MHz	✔				

			Applicable technologies				
Region	**Countries**	**Frequency bands**	**GSM**	**CDMA**	**UMTS**	**LTE**	**WIMAX**
Africa, Asia-Pacific, Caribbean, Central America, Europe, Middle East, Oceania, South America	Andorra, Burkina Faso, Burundi, Cameroon, China, Comoros, Cook Islands, Cuba, Djibouti, East Timor, East Timor, Ethiopia, Falkland Islands, Faroe Islands, Fiji, French Polynesia, Ghana, Gibraltar, Greenland, Guyana, Iraq, Kazakhstan, Libya, Mali, Micronesia, Morocco, Myanmar, Niger, Norfolk Island, North Korea, Papua New Guinea, Rwanda, Saint Pierre and Miquelon, Samoa, Sao Tome and Principal, Saudi Arabia, Senegal, Solomon Islands, Swaziland, Togo, Tonga, Vanuatu, West Bank/Gaza Strip, Yemen, Zambia, Zimbabwe	900 MHz	✓				
Africa, Asia-Pacific, Caribbean, Europe, Middle East, Oceania	Afghanistan, Albania, Algeria, Angola, Armenia, Aruba, Australia, Austria, Azerbaijan, Bahrain, Bangladesh, Belarus, Belgium, Benin, Bhutan, Bosnia and Herzegovina, Bulgaria, Cameroon, Cape Verde, Central African Republic, Congo, Cote d'Ivoire, Croatia, Cyprus, Czech Republic, Denmark, Egypt, Eritrea, Estonia, Finland, France, French Guiana, French Westside, Gabon, Gambia, Gaza Strip/West Bank, Georgia, Germany, Greece, Guinea-Bissau, Guinea, Holy See, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Ireland, Isle of Man, Israel, Italy, Jamaica, Jersey, Jordan, Kenya, Kuwait, Kyrgyzstan, Laos, Latvia, Liberia, Liechtenstein, Lithuania, Luxembourg, Macau, Macau, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Malta, Mayotte, Mongolia, Montenegro, Mozambique, Namibia, Nepal, Netherlands Antilles, Netherlands, New Zealand, Nigeria, Norway, Pakistan, Palau, Philippines, Poland, Portugal, Qatar, Reunion, Romania, Russia, San Marino, Serbia, Seychelles, Sierra Leone, Singapore, Slovakia, Slovenia, Somalia, South Africa, Spain, Sri Lanka, Sudan, Suriname, Sweden, Switzerland, Syria, Taiwan, Tajikistan, Tanzania, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, United Arab Emirates, United Kingdom, Uzbekistan, Vietnam	900 MHz/1800 MHz	✓			✓	
Asia, Caribbean	Aruba, Barbados, Dominican Republic, Thailand	900 MHz/ 1800 MHz/ 1900 MHz	✓				
Caribbean	Antigua and Barbuda, Dominica	900 MHz/850 MHz/ 1900 MHz	✓				
Caribbean, South America	Brazil, British Virgin Islands, Cayman Islands, Dominican Republic, Jamaica, Saint Kitts and Nevis, Saint Lucia, Turks and Caicos Islands	900 MHz/850 MHz/ 1900 MHz/ 1800 MHz	✓				
Island - British Channel	Guernsey	900 MHz/850 MHz/ 1800 MHz	✓				
Eurasia, Oceania	Armenia, Croatia, Denmark, Estonia, Finland, France, Hong Kong, Poland, New Zealand, Romania, Slovenia, Sweden, Australia	900 MHz/2100 MHz			✓		

			Applicable technologies				
Region	**Countries**	**Frequency bands**	**GSM**	**CDMA**	**UMTS**	**LTE**	**WIMAX**
Asia	Japan	1500 MHz				✔	
North America	USA	1.6 GHz				✔	
Asia	Japan	1.7 GHz				✔	
Asia, North America	Canada, Japan, USA	1700 MHz			✔		
North America	USA	1.7 GHz/2.1GHz				✔	
Europe	Poland	1800 MHz	✔				
Caribbean, North America, Oceania, South America	American Samoa, Bahamas, Belize, Bermuda, Brazil, Chile, El Salvador, Guatemala, Mexico	1900 MHz	✔				
Africa, Asia, Caribbean	Algeria, Argentina, Aruba, Barbados, Bermuda, Brazil, Cayman Islands, Chile, Dominican Republic, Ecuador, El Salvador, Guam, Guatemala, Jamaica, Philippines, Puerto Rico, Uruguay	1900 MHz		✔			
Asia, Caribbean, North America, South America	Barbados, Canada, Indonesia, Mexico, Trinidad/Tobago, USA	800 MHz/1900 MHz		✔			
Africa	Nigeria	cdma2000 1x/EV-DO		✔			
Africa, Caribbean, Eurasia, Middle East, Oceania, South America	Albania, Andorra, Angola, Armenia, Aruba, Australia, Austria, Azerbaijan, Bahrain, Bangladesh, Belarus, Belgium, Bosnia, Brazil, Brunei, Bulgaria, Cambodia, China, Croatia, Cyprus, Czech Republic, Denmark, Egypt, Estonia, Finland, Georgia, Germany, Ghana, Gibraltar, Greece, Guernsey, Hong Kong, Hungary, Iceland, India, Indonesia, Iraq, Ireland, Isle of Man, Israel, Italy, Japan, Jersey, Kenya, Kuwait, Laos, Latvia, Lauritius, Libya, Liechtenstein, Lithuania, Luxembourg, Macau, Macedonia, Malaysia, Malta, Moldova, Monaco, Montenegro, Morocco, Namibia, Nepal, Netherlands, Nigeria, Norway, Pakistan, Philippines, Poland, Portugal, Qatar, Romania, Russia, Saudi Arabia, Serbia, Seychelles, Singapore, Slovak Republic, Slovenia, South Africa, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Taiwan, Tajikistan, Tanzania, Thailand, Turkey, Uganda, Ukraine, United Arab Emirates, United Kingdom, Zimbabwe	2100 MHz			✔		
Europe	Germany	2.1 GHz/800 MHz/ 2.6 GHz/1800 MHz				✔	

			Applicable technologies				
Region	**Countries**	**Frequency bands**	**GSM**	**CDMA**	**UMTS**	**LTE**	**WIMAX**
Oceania	Australia	2.1 GHz/1800 MHz				✓	
Asia	India	2.3 GHz				✓	
Eurasia	Georgia, Indonesia, Malaysia, Russia, Tajikistan	2.3 GHz					✓
Eurasia	Russia	2.3 GHz/2.4 GHz				✓	
Asia	China	2.3 GHz/2.5 GHz				✓	
Europe	Denmark	2.5 GHz				✓	
Africa, Eurasia, North America	Angola, Canada, Russia, USA	2.5 GHz					✓
Africa, Central America, Eurasia, South America	South Africa, Argentina, Chile, Colombia, Hong Kong, Malaysia, Lithuania, Uzbekistan, Austria, Finland, Germany, Jersey, Netherlands, Sweden	2.6 GHz				✓	
Europe	Finland	2.6 GHz/1.8 GHz				✓	
Europe	Germany	2.6GHz/2.1GHz				✓	
Asia	Indonesia	3.3 GHz					✓
Europe	Germany	3.4 GHz-3.6 GHz					✓
Africa, Eurasia, North America, Oceania	Italy, Bulgaria, Canada, Colombia, Croatia, Dominican Republic, Ethiopia, Macedonia, Malta, The Netherlands, New Zealand, Nigeria, Russia, Sri Lanka	3.5 GHz					✓
Europe	Estonia	3.5 GHz – 3.6 GHz					✓
Oceania	Australia	5 GHz					✓
Asia, Caribbean, Middle East	Cayman Islands, Indonesia, Jamaica, Saudi Arabia	802.16d					✓
Africa, Caribbean, Eurasia, North America	Cayman Islands, Bangladesh, Canada, Indonesia, Libya, Russia	802.16e					✓

Biographies

Robert Cameron
Applications engineer

Robert is an invaluable resource to CommScope customers, providing insight and training on the latest solutions and how best to implement them. He is also responsible for providing background technical information and troubleshooting. He has spent the past 17 years in the RF industry, working in amplifier, antenna and RF system design. Robert's career began as part of an ambitious startup company, where he designed cellular network repeaters before moving into system design and project management to round out his expertise. He has managed several high-profile projects, including the two stadiums where the Kansas City's Chiefs and Royals play football and baseball, respectively, as well as in-building systems for the Library of Congress and the World Bank. He has also managed installations for the US military and several key airports and large banks. Robert holds a B.S. in Electrical and Computer Engineering from Ohio State University, with a focus on RF.

Fred Hawley
Principal reliability engineer

Fred has spent more than 35 years in telecommunications and military reliability engineering. Currently, he focuses on reliability prediction and modeling for CommScope products. His expertise helps direct the development of such diverse solutions as power amplifiers, remote radio heads and other base station- and tower-mounted wireless communication equipment. His work helps ensure superior performance from every solution CommScope builds. Fred holds a MSEE from Columbia University in New York, and is an active member of IEEE.

Mark Hendrix, P.E.
Engineering manager, new product development

Mark is responsible for directing innovation efforts in wireless communications systems and modular data centers for CommScope, with particular focus on thermal design, power systems and other efficiency drivers. He brings 27 years of expertise in electronic packaging, with strong backgrounds in both defense electronics and telecommunications for such names as Texas Instruments, Fujitsu and Xtera Communications. Mark holds eight U.S. patents and is a registered Professional Engineer in the State of Texas. He holds a B.S. in Mechanical Engineering from Clemson University, and an M.S. in Mechanical Engineering from Southern Methodist University.

Chris Hills
Technical director, microwave systems

Chris is an important part of CommScope's Andrew Solutions team, offering leadership in the field of microwave antennas and array antennas and aligning new technology to marketplace conditions. In an earlier role as RF Engineering Manager for Andrew, Ltd., Chris devoted nearly 20 years to advancing antenna design, resulting in the development of the highly successful ValuLine family of antennas used the world over for point-to-point communications, as well as other significant intellectual property. Chris earned his B.S. degree with Honors in Electronic and Electrical Engineering from the University of Surrey in the United Kingdom. He holds multiple patents and serves as an active member of IEEE and IET.

Erik Lilieholm
Applications engineering manager, wireless network solutions

Erik's diverse background in North America's wireless communications industry dates back to the launch of the first cellular communications networks. He has built his expertise with Allen Telecom, LGP Telecom and Ericsson. With more than 25 years in RF design, product management and technical marketing, Erik provides critical leadership to CommScope's families of wireless solutions, helping each product fulfill its specific role and customer need. He holds several patents in the field of RF filter technology. Erik earned a Master of Science degree in Electrical Engineering from the Royal Institute of Technology in Stockholm, Sweden, and an MBA from the University of Nevada, Reno.

Louis Meyer, P.E.
Director of technical marketing—RF path

Louis has spent a lifetime advancing RF technology, taking it from the drawing board to practical use. Over the years in various roles with Allen Telecom, Andrew Ltd. and CommScope, Louis was responsible for supporting the sales teams for such solutions as remote antenna control systems, transmission lines, diplexers and other important components. Prior to joining Allen Telecom, Louis worked with Decibel Products as V.P. Antenna Design and V.P. International OEM Relations. Earlier, Louis worked with Harris Corporation in RF communications and Bendix Corporation in their missile systems division. Louis holds five patents and has been active as a chair and vice-chair of the TIA's TR-8.11 Antenna Standards sub-committee. He earned his B.S. in Electrical Engineering from Marquette University in Milwaukee, Wisconsin and is currently a registered Professional Engineer in the state of Texas.

Larry Seper
Director of construction services

Larry provides telecommunications installation solutions for CommScope's customers, supporting products and systems such as antennas and transmission lines, power amplifiers, remote radio heads and PIM/Sweep testing procedures. He also focuses on civil site work, helping establish the physical foundations of wireless communication as well as its technological foundations. Larry brings more than 36 years of financial and operations management experience to bear for CommScope's customers, and is a key player in making certain that every CommScope solution is the right solution. Larry holds a B.S. in Accounting from Marquette University in Milwaukee, Wisconsin and is an active member of AICPA.

Tom Sullivan

Director, global new product introductions

Tom currently oversees new product introductions for CommScope, and he's served in many roles since joining Andrew, Ltd. in 1982 as an antenna design engineer. In that position, Tom developed the antennas and supporting devices customers needed to build point-to-point communications networks. He has also served as a Global Sales Manager for OEMs including Ericsson, Nokia, Lucent and Motorola. He also worked in quality control and product line management in support of CommScope's successful HELIAX cable and connector solutions. Tom is an active member of IEEE, and holds a B.S. in Electronic Engineering Technology from DeVry Institute of Technology, and an MBA in International Business from St. Xavier University in Chicago, Illinois.

Dr. Junaid Syed

Electrical engineering manager, microwave systems

Junaid directs new product development for CommScope in the areas of microwave and millimeter wave antenna systems, flexi waveguides and waveguide components that support mobile backhaul systems. He brings 26 years of international experience in the telecommunication and defense industries. He holds seven patents and is a current member of SE Scotland IET and Technical committees. He also represents CommScope as a technical committee member with ETSI. Junaid earned his B.S. in Aero Sciences from Punjab University with Silver Medal honors, and a Bachelor of Engineering degree in Electronics/Avionics from NED University of Engineering and Technology with Gold Medal honors, both in Pakistan. He earned his Ph.D. in Microwave and Millimeter Wave from the University of London and conducted his post-doctoral research on reflect array antenna design at Queen's University Belfast, both in the United Kingdom.

Dr. Keith Tappin—In Memoriam

Director of engineering, microwave systems

It is with heavy hearts that we share the news of Dr. Keith Tappin's sudden passing. His significant influence on this book is one of many positive contributions Keith made as a part of the CommScope family. He was a first-rate engineer, manager and leader—a warm man with a great sense of humor and a genuine passion for his profession. Please join us as we offer our condolences to Keith's family, friends and colleagues—and our gratitude for the life he shared with us.

Keith was responsible for developing new products and processes related to advanced passive microwave applications for CommScope's Microwave Systems group. Keith built his expertise in microwave components and antenna design for 15 years, focusing heavily on defense and commercial communications systems. Prior to joining CommScope, Keith conducted research at the University of Illinois (U.S.) and The University of Birmingham (UK), where he investigated metallic radiation interactions and developed high-temperature alloys for aerospace applications. Keith published more than 20 technical papers and held two patents. He earned his degree in Metallurgy and Materials Science from the University of Liverpool in the UK, where he later completed his Ph.D.

Glossary

alternating current (AC)
An electrical current that changes polarity (i.e., direction) 50 to 60 times per second. It offers significant efficiencies when transmitted across power lines, making it the standard current for household use. *See also: direct current.*

Andrew integrated management and operating system (A.I.M.O.S.)
The network management software solution for all CommScope-distributed antenna systems. Part of the Andrew Solutions portfolio, A.I.M.O.S. performs configuration fault and inventory via SNMP for alarm forwarding.

antenna
The portion of an RF system that radiates radio energy into space and collects it from space.

Antenna Interface Standards Group (AISG)
An industry group comprised of more than 40 top manufacturers and service providers from all over the world. AISG was founded in 2001 and publishes universally accepted industry protocols for communications between base stations and tower-based equipment, such as antennas and tower-mounted amplifiers.

attenuation
Measured in decibels (dB), attenuation is the loss of power experienced by an RF signal as it moves from one point to another. Transmission line attenuation is expressed in either decibels per 100 feet (dB/100 feet) or decibels per 100 meters (dB/100m) of cable length.

automatic transmission power control (ATPC)
A system that dynamically raises transmission power to overcome the effects of interference.

azimuth coordinate system
The polar coordinate system used in the field by RF engineers and surveyors to map the radiation pattern of antennas. *See also: radiation pattern, spherical coordinate system.*

backhaul
The process of connecting two ends of a transmission through a central routing point.

bandpass cavity
A “frequency filter” that limits the channels that pass through the filter to a radio receiver’s select set of frequencies. Other frequencies are prevented from passing. Most devices have multi-stage bandpass cavities that filter out different frequencies at each stage.

bandpass duplexer
A duplexer that uses multiple bandpass cavities to separate transmitter and receiver signals, allowing for simultaneous two-way communications. *See also: Duplexer, Duplex Communications, Bandpass Cavity.*

bypass (pass-through) configuration
A single-band tower-mounted antenna with an integrated diplexer that adds a secondary, non-amplified RF path to the system.

co-channel dual-polar (CCDP) operation
Using both horizontal and vertical polarity of a single frequency to double available bandwidth.

co-siting solutions
The technology and techniques that allow cellular base stations and air interfaces to share architecture and operate within limiting factors of their locations.

coaxial cable
A transmission line built to prevent interference while carrying multiple signals. Coaxial cable consists of an inner core conductor and an outer sleeve conductor, separated by a nonconductive dielectric layer. Coaxial cable is often used to connect antennas to base stations. *See also: dielectric layer.*

dielectric layer
The insulated, tube-shaped layer separating a coaxial cable’s inner and outer conductors. Dielectrics may be made of solid material, flexible foam or open air channels supported by nonconductive spacers. *See also: coaxial cable.*

direct current (DC)
An electrical current that runs continuously in a single direction, making it well suited for use in motors and electronic components such as semiconductors. Batteries also produce DC current. *See also: alternating current.*

distributed antenna system (DAS)
A network of nodes serving a specific place, area or building. They connect through a central base station for backhaul out to the public network.

dummy load
A simulated power load applied to an electrical system for testing purposes. *See also: voltage standing wave ratio (VSWR).*

duplex communications
A transmitter and receiver that work at the same time on the same RF device, allowing two-way communications. *See also: duplexer.*

duplexer
A device situated between a duplexed antenna and its associated transmitter and receiver that provides isolation between the two signals. See also: Duplex Communications.

electrical potential
The difference in electrical charge between two points in space, measured in volts. The greater the difference, the higher the potential – and therefore, the greater the voltage. *See also: volt.*

electrical tilt antenna
An antenna fitted with actuators that can adjust its tilt relative to the ground. These adjustments affect gain, or performance, of the antenna within defined geographical areas.

environmental factors
Circumstances of temperature, sunlight exposure, humidity and other specific characteristics of an installation. Environmental factors play a large role in determining what kind of antenna, transmission line, power and other components are ideal for use in a particular location.

failures in time (FITs)
The number of expected component failures per billion operating hours. See also: reliability.

flat fading
Total signal loss caused by atmospheric refraction. It is the result of a signal being bent completely out of its LOS connection with its receiver.

frequency multiplexing
A configuration that connects multiple base station services that operate in separate bands to multiple antennas via a single feeder cable and its associated couplers.

grounding
Measures taken to control and facilitate the path of an electrical discharge from its source to the ground, avoiding potential damage to sensitive equipment along the way. Grounding is a key element in protecting an installation from damage by lightning strike or other hazards.

guard bands
Narrow gaps inserted into the bandwidths managed by the low loss combiner (LLC) to distinguish between different signals riding on the same bands. *See also: isolation, low loss combiner, transmitter noise.*

horizontal separation
The practice of placing a transmitter's antenna a certain distance from the same device's receiving antenna to achieve the necessary isolation. *See also: duplex communications, isolation, vertical separation.*

in phase
A state of operation referring to multiple antennas radiating together at precisely the same time and rate.

integrated power systems
Space-saving combinations of related components, built into a single device for easy installation.

interoperability testing (IOT)
The practice of testing for operational problems in a cell site that employs equipment from multiple manufacturers.

isolation
The amount of separation achieved between the transmitter and receiver in a duplex communication system. In general, more isolation translates to less interference between the two functions, and correspondingly clearer communications. *See also: duplex communications, horizontal separation, vertical separation.*

line of sight (LOS)
The unobstructed space between transmitter and receiver. Longer hops must even account for the curve of the Earth as an obstruction.

low loss combiner (LLC)
A device in the RF path that permits the simultaneous operation of multiple transmitters on a single antenna. It applies guard bands and bandpass cavities to provide the necessary isolation between signals. *See also: bandpass cavity, guard bands, isolation.*

nonlinearity
A location within an electrical circuit where voltage does not remain consistently proportional to power, generally caused by imperfect connections between components and cables or damage to a cable's structure.

ohm
The unit of measurement of a material's electrical resistance. When applied to discussions of RF transmission lines, ohms refer to the inherent, or characteristic, loss of strength a signal encounters as it passes along a length of cable.

pass-through (bypass) configuration
A single-band tower-mounted antenna with an integrated diplexer that adds a secondary, non-amplified RF path to the system.

passive intermodulation (PIM)
A potential side effect of having more than one high-powered signal operating on a passive device such as a cable or antenna. PIM occurs at non-linear points in a system such as junctions, connections or interfaces between dissimilar metal conductors, creating interfering frequencies that can decrease efficiency. The higher the signal amplitude, or power, the greater the effect. *See also: nonlinearity.*

quarter-wave shorting stub
A device inserted into the connection between transmission line and antenna that does not affect normal frequencies, but will immediately short—and safely dissipate energy—when lightning frequencies attempt to cross. *See also: grounding.*

radiation pattern
The three-dimensional shape of an antenna's strongest signal transmission.

radome
A wind- and water-proofed fabric or plastic cover that protects an antenna from the elements.

receiver desensitization
Interference caused by unwanted frequencies entering a receiver's upper stage passbands. These errant signals create electrical variances that impede the receiver's operation. *See also: bandpass cavity.*

reliability
The probability of a device working correctly over a defined length of time, operating under specified conditions. *See also: failures in time (FITs).*

remote radio head (RRH)
A recent advance in base station architecture that separates a cell site base station's RF and baseband functions for improved efficiency. RRH advantages include no active cooling requirement, lower overall power loss, less weight on the tower and compact size.

resonant frequency
The natural tendency of a system to oscillate with larger amplitude at particular frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations.

same-band combining (SBC)
A base station configuration that allows multiple services to share the same bands.

service company
A cell site development partner responsible for actual construction on the site, including antenna towers, concrete footers and pads, security fencing, and equipment shelters.

Shannon's Law
Created by Claude Shannon and Ralph Hartley, this law establishes a theoretical limit to how much data can be reliably pushed through a given amount of bandwidth.

signal polarization
The orientation of a signal's electric field relative to the ground. It may be horizontal or vertical.

spherical coordinate system
A geometric polar coordinate system used to mathematically map the radiation pattern of antennas. *See also: azimuth coordinate system, radiation pattern.*

split-mount radio system
A two-stage connection that lets microwave radios located in an indoor unit (IDU) receive and transmit through an antenna fitted with an outdoor unit (ODU).

transmission lines
In RF applications, the physical medium that conducts RF power from one point to another, usually between a base station and an antenna.

transmitter noise
Interference experienced by a receiver as a result of transmission power "leaking" into other nearby frequencies.

vertical separation
The practice of placing a transmitter and receiver in separate locations on a single antenna, allowing the height difference to achieve the necessary isolation. *See also: duplex communications, horizontal separation, isolation.*

volt
A measurement of electric potential difference between two points in a path. Voltage is sometimes referred to as "pressure," because it shares many characteristics with pressure in a water pipe.

voltage polarity (+ and –)
The positive (+) and negative (–) designations of voltage refer to which polarity of a circuit is measured; in terms of actual power produced, the distinction is meaningless.

voltage standing wave ratio (VSWR)
A key measurement of cable performance and signal quality. It quantifies the amount of signal reflected backward along a cable to its source. Theoretically, perfect operation yields a VSWR value of 1.0, or "unity," meaning zero reflections.

Yagi antenna
Also known as a Yagi-Uda antenna, this is a common type of directional antenna, first created in Japan in 1926 by Hidetsugu Yagi and Shintaro Uda.

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- Base station antennas
- Co-siting solutions
- Remote radio heads
- Transmission and receiving isolation systems
- Transmission lines
- Passive intermodulation (PIM) fundamentals
- Microwave backhaul
- Powering wireless networks
- Distributed antenna systems
- Lightning protection

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Technology is reshaping the way we live, learn and thrive. The epicenter of this transformation is the communications network—our passion. CommScope designs and builds the connectivity for the world's most advanced networks.

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